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Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection

Volume I: Final Report

U.S. Department of Transportation
Federal Highway Administration

Research and Development
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FOREWORD

This report is one volume in a three-volume series which presents the results of a series of on-the-road studies investigating the perception-reaction times (PRT) of older and younger drivers. Perception-reaction time is an important component of highway design equations and was investigated with respect to stopping sight distance, intersection sight distance, and decision sight distance. Although differences were found in PRT between the age groups, the current American Association of State and Highway Transportation Officials (AASHTO) standards used in these equations were found to accommodate the 85th percentile for both older and younger drivers. Gap and lag acceptance was also investigated as a possible alternate design model for sight distance equations. Younger subjects accepted shorter gaps and rejected lags later than older subjects. The results of this study will be useful to researchers, planners, and others working in the area of highway and older driver safety.

Sufficient copies of these reports are being distributed to provide a minimum of two copies to each Federal Highway Administration regional and division office, and five copies to each State Highway Agency. Direct distribution is being made to division offices.

Lyle Saxton

Lyle Saxton, Director
Office of Safety and Traffic
Operations Research and Development

NOTICE

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16. Abstract

Four on-road experiments investigated whether the assumed values for driver perception-reaction time (PRT) used in AASHTO design equations adequately represent the range of actual PRT for older drivers. The Case III (stop controlled) intersection sight distance (ISD) experiment found that older drivers did not have longer PRT than younger drivers; 85th percentile PRT closely matched the AASHTO design equation value of 2.0 s. In the stopping sight distance (SSD) experiment, involving brake reaction times to an unanticipated event (crash barrel suddenly rolling toward roadway), there were apparent differences in the distribution of PRT among age groups. Younger drivers accounted for most of the fastest PRT, but there were no age differences in the 50th or 85th percentiles. All observed PRT were encompassed by the current AASHTO design value of 2.5 s. The decision sight distance (DSD) experiment measured when drivers recognized the need to make a lane change maneuver, from the first visibility of the roadway cue used by the driver. Although observed DSD values were generally longer with increasing driver age, the 85th percentile PRT for all age groups were well below AASHTO design assumptions. The final experiment collected judgments about the acceptability of gaps and lags in traffic. Younger subjects accepted shorter gaps and rejected lags later than older subjects. Based on these findings, and consideration of the implications of changes in PRT for sight distance requirements, no changes to design PRT values, based on older driver performance, were recommended for ISD, SSD, or DSD. Alternative models for ISD, based on gap acceptance or lag rejection, were explored. Based on limited data, it is not clear whether these models offer any significant benefits to the current AASHTO model.

This volume is the first in a series, the others in the series are:
Volume II FHWA-RD-93-169 Appendixes (unpublished)
Volume III FHWA-RD-93-170 Executive Summary

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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TABLE OF CONTENTS
Volume I

LIST OF FIGURES
Volume I

LIST OF TABLES
Volume I

LIST OF TABLES
Volume I
(continued)

TABLE OF CONTENTS
Volume II

LIST OF FIGURES
Volume II

Figure | Page

LIST OF FIGURES
Volume II
(continued)

LIST OF FIGURES
Volume II
(continued)

LIST OF FIGURES
Volume II
(continued)

LIST OF FIGURES
Volume II
(continued)

LIST OF TABLES
Volume II

Table | Page

CHAPTER 1. INTRODUCTION

HIGHWAY SAFETY CONCERN ABOUT AGING AND SLOWING

This report addresses the question of whether various important highway design criteria adequately match the capabilities of older drivers. Equations for determining the minimum necessary sight distance for different driving situations are based in part on assumptions about how long it takes a driver to perceive, decide, and react. Because there is a general slowing of behavior with age, there is concern about whether present design values are adequate for older drivers.

In order for the highway system to operate efficiently and safely, its design criteria must match the characteristics and abilities of the drivers who use it. Such a match is not necessarily the case for "older" drivers (e.g., those over age 65). A review of the technical basis of a wide variety of standards and practices in the Manual on Uniform Traffic Control Devices found that, while many had virtually no empirical basis, those that were based on driver performance data came particularly from younger drivers.[1] Likewise, a review of numerous highway design and operational standards that could be affected by driver characteristics identified serious concerns related to capabilities that decline with age.[2] Recent studies, reviews, and conferences on older drivers have focused concern on the adequacy of highway design and operational practices for this group of drivers.[3,4] A failure of design practices to match the requirements of older drivers may make aspects of the driving task more difficult for them, increase their accident potential, cause operational conflicts and lack of conformity with other traffic, and discourage personal mobility. Furthermore, as the older driver accounts for increasingly greater proportions of the Nation's driving miles, the implications for safety and operations of the highway system as a whole become critical. The number of people in the U.S. aged 65 and older is projected to approximately double in the next 40 years, accounting for over one-fifth of the population.[3] Furthermore, successive cohorts of the population are increasingly "motorized," so that their proportion of roadway travel can be expected to grow in even greater proportion than their proportion of the population.[5]

The difficulties some older drivers may face with the roadway system is also suggested by their increased collision involvement rates. There is a well-established U-shaped relationship between driver age and per-mile accident involvement rates, with older drivers having greater rates of accidents, injuries, and fatalities than middle-aged drivers.[3,6] This is despite that fact that older drivers self-regulate their driving exposure, so that the miles they do drive tend to exclude the most risky conditions (night, heavy traffic, inclement weather, unfamiliar areas). The magnitude of enhanced risk with age is the subject of debate, and to some extent may reflect greater vulnerability to injury, but it is also the case that given an accident involvement, the older driver is more likely to be found at-fault and that the relative frequency of various accident types is different for older and younger drivers.[6,7,8] The substantial literature on older driver accidents indicates that this group has its own distinct, and substantial, safety concerns. This underscores the need for highway design and operational practices to take into account the requirements of the older driver.

Among the many aspects of highway design criteria is the key concept of "sight distance." There are various types of sight distance, for different driving situations, such as stopping sight distance, intersection sight distance, railroad-highway grade crossing sight distance, decision sight distance, and passing sight distance. Sight distance is the distance a driver must be able to see in order to have enough time to make a required driving maneuver. Sight distance design equations are based on two components: a time to perceive the need for a response and initiate that action (the "perception-reaction time," or PRT); and a time to actually execute the driving response, once initiated (the "maneuver time"). Thus, assumptions about PRT are central to highway design and operations, and an individual's PRT in a given situation is an important element in highway safety.

Perception-reaction time itself is not a unitary concept, but is composed of a sequence of underlying processes, including visual search, recognition, evaluation and decision making, response initiation (processing delay prior to initiation of movement), and response execution (the initial overt motor response, e.g., foot to brake pedal). All of these component processes are known to be influenced by age. One of the most well-established laboratory research findings in gerontology is a broad, general slowing of many behaviors with advancing age. Thus a serious question has been raised as to whether the PRT values used in highway design and operations, based on consideration of the general population, are adequate to meet the requirements of older drivers. This is the central issue of the research described in this report.

Although some degree of "slowing" with age is typical, this does not necessarily imply that current traffic engineering practice is inadequate with respect to the sight distance requirements of older drivers. A number of reasons why current practice might yet be adequate have been discussed by Lerner.[9] Briefly, these include self-selection among older drivers, the potentially small magnitude of response time differences, the ability of older drivers to find compensatory strategies, the "overlearned" nature of many driving responses, age differences in driving style, and the degree of "cushion" in current highway design equations due to combinations of worst-case assumptions. Thus while there is cause for concern about the adequacy of various highway design practices for older road users, it is unwarranted to assume that current practice must be inadequate. Given the widespread implications of any change to design standards, it is important to empirically determine whether, and to what extent, current design equations may fail to meet the needs of the older driver population. The general objective of the work described in this report was to empirically determine whether the design models and assumed parameter values currently used for several key sight distance situations are adequate, based on the observed PRT of older drivers.

THE ROLE OF PERCEPTION-REACTION TIME IN HIGHWAY DESIGN

Perception-reaction time (PRT) is a key concept in models of driver behavior and highway design, underlying many current design criteria. It is explicitly considered in various sight distance elements including:

- Stopping sight distance (SSD).
- Decision sight distance (DSD).
- Intersection sight distance (ISD).
- Railroad-highway grade crossing sight distance.
- Passing sight distance.

Sight distance requirements, and therefore PRT, form the basis for some specific geometric design elements. For example, crest and sag vertical curve designs consider sight distance in determining the length of curve, as does the standard on lateral clearance to sight obstructions on horizontal curves. On the operational side, PRT is considered in determining yellow change and clearance intervals for traffic signal timing.

While there are several types of driver PRT, this project limits the evaluation of PRT for older drivers to three situations: (1) SSD, (2) DSD, and (3) ISD. Issues concerning PRT for each of these elements are discussed below.

Stopping Sight Distance. SSD is the basic sight distance requirement for vertical and horizontal curve design on highways. Not only is the SSD important to vertical and horizontal curve design, it forms the basis for many other highway design and operational criteria including warning sign placement, intersection sight distance, and railroad-highway grade crossing sight distance.

SSD as defined in the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets* (usually referred to as the "Green Book") is the minimum sight distance required for a vehicle traveling at or near design speed to stop before reaching a stationary object in its path.[10] It has two components: brake-reaction distance (distance traversed by the vehicle from the instant of object detection necessitating brake application to the instant vehicle brakes are applied) and braking distance (distance required for the vehicle to come to a complete stop). It sets minimum sight distances along highways. Mathematically SSD is expressed as:

$$d = 1.47PV + \frac{V^2}{30(f \pm G)} \tag{1}$$

where

d	=	stopping sight distance (ft),
P	=	brake reaction time (s),
V	=	vehicle design speed (mi/h),
f	=	coefficient of friction between tires and roadways, and
G	=	grade (%/100).

It is explicitly considered in railroad-crossing sight distance and implicit in Case II intersection sight distance (i.e., intersection sight distance where there is a yield control on the minor street only), and, as noted above, is the basis for sag and crest vertical curve design.

The PRT for SSD requires a simple decision and response. Based on the AASHTO policy, the PRT is specified as 2.5 s.

__Decision Sight Distance__. As a geometric design element, DSD is intended to provide the driver with sufficient sight distance to detect an unexpected or difficult-to-perceive information source or hazard, recognize the situation and its threat potential, and complete an appropriate maneuver safely and efficiently. These sight distance criteria were established for complex highway situations such as interchanges, lane drops, high-speed merges, toll booths, and intersections where unusual or unexpected maneuvers are required. For these types of situations the motorist needs sufficient time to detect and comprehend the situation, decide on an appropriate maneuver, and accomplish the maneuver in a safe manner. Because DSD is defined for a less restrictive maneuver than the sudden braking assumed for SSD, DSD values are substantially longer and provide an additional margin for error.

Based on the work of McGee et al., the 1984 AASHTO Green Book provided DSD for a lane change maneuver as shown in table 1.[11,12] These DSD are based on a) a pre-maneuver component (PRT component) ranging from 5.7 s to 10.0 s, and b) a maneuver component varying from 4.0 to 4.5 s for design speeds from 20 mi/h to 70 mi/h (32 km to 113 km). As can be seen in table 1, these values were computed for a lane change maneuver only.

Table 1. Decision sight distances, 1984.[12]

	Pre-maneuver Times (s)		Maneuver	Summation	Design Sight Distance ft (m)*	
Design Speed mi/h (km/h)*	Detection & Recognition	Decision & Response Initiation	Maneuver (Lane Change)	Seconds	Computed	Rounded for Design
30 (48)	1.5-3.0	4.2-6.5	4.5	10.2-14.0	449-616 (137-188)	450-625 (137-191)
40 (64)	1.5-3.0	4.2-6.5	4.5	10.2-14.0	598-821 (182-250)	600-825 (183-252)
50 (81)	1.5-3.0	4.2-6.5	4.5	10.2-14.0	748-1027 (228-313)	750-1025 (229-313)
60 (97)	2.0-3.0	4.7-7.0	4.5	11.2-14.5	986-1276 (301-389)	1000-1275 (305-389)
70 (113)	2.0-3.0	4.7-7.0	4.0	10.7-14.0	1098-1437 (335-438)	1100-1450 (336-442)

*mi = km x 0.621, ft = m x 3.28

In the latest AASHTO policy, these DSD values were revised based on road type and maneuver.[10] The road types are rural, suburban, and urban, and the maneuvers are either a stop or a change in speed, path or direction. The roadway types and maneuvers considered for calculating the DSD values which are presented in table 2 are:

- Avoidance Maneuver A: Stop on rural road.
- Avoidance Maneuver B: Stop on urban road.
- Avoidance Maneuver C: Speed/path/direction change on rural road.
- Avoidance Maneuver D: Speed/path/direction change on suburban road.
- Avoidance Maneuver E: Speed/path/direction change on urban road.

Table 2. Decision sight distances, 1990.[12]

Design Speed mi/h (km)*	Decision Sight Distances for Avoidance Maneuver - ft (m)*				
	A	B	C	D	E
30 (48)	220 (67)	500 (153)	450 (137)	500 (153)	625 (191)
40 (64)	345 (105)	725 (221)	600 (183)	725 (221)	825 (252)
50 (81)	500 (153)	975 (297)	750 (229)	900 (275)	1025 (313)
60 (97)	680 (207)	1300 (397)	1000 (305)	1150 (351)	1275 (389)
70 (113)	900 (275)	1525 (465)	1100 (336)	1300 (397)	1450 (442)

*mi = km x 0.621, ft = m x 3.28

A review of the values, shows the DSD values are longer for the urban roadways for all speeds. This results from the assumption that urban situations are more complex and, therefore, require more time for information processing. DSD varies depending on the maneuver type, vehicle speed, and location of avoidance maneuver. For design speeds from 30 to 70 mi/h (48 to 133 km/h), the PRT values used range from 5.7 to 6.7 s for rural situations and from 9.5 to 10.0 s for urban situations. The AASHTO policy states: "Because of the additional safety and maneuverability these lengths yield, it is recommended that DSD be provided at critical locations or that these points be relocated to locations where DSD is available."

The field studies upon which the PRT calculations were based were very limited and gave no specific consideration to the older driver. However, it is in precisely the types of highway situations for which the DSD criteria were developed that older drivers may tend to have more difficulties related to information processing and decision making. Therefore, it is appropriate that the PRT for decision sight distance be re-evaluated with specific consideration given to the older driver.

Intersection Sight Distance. For at-grade intersections there are six specific cases defined in AASHTO's *A Policy Geometric Design of Highways and Streets*:

1. Case I - No intersection control
2. Case II - Yield control on minor road
3. Case IIIA - STOP control, driver will cross intersection
4. Case IIIB - STOP control, driver will turn left
5. Case IIIC - STOP control, driver will turn right
6. Case IV - Signal control

For each of these situations there is a PRT considered. For Case I and Cases IIIA, B and C, 2.0 s is specified in the AASHTO policy. However, for Case IIIA the AASHTO policy states that "in urban or suburban areas....a somewhat lower value might apply;" values of 0.5 and 1.0 s are mentioned. While not explicitly stated in the AASHTO policy, Case II is based on SSD and, therefore, the PRT would be 2.5 s.

The PRT for Cases II and III was the subject of a FHWA study.[13] The researchers concluded that 2.0 s was satisfactory for Case IIIA, but the PRT for Cases IIIB and C be increased to 2.5 s. They also found no significant age differences for any of the PRT measures. Subjects were compared in 6 age categories, spanning from 16 to over 65 years old. For the oldest group (65+), the age range was not specified.

Of the six specific intersection sight distance cases, the three Case III scenarios may be of greatest interest for addressing older driver problems for the following reasons. While PRT for Case I could be problematic for older drivers, there are few of these intersections. They are usually in certain low volume residential areas or in isolated rural areas where the vast majority of drivers are very familiar with the intersection. Since Case II is an application of SSD, its PRT can be evaluated within that criterion.

The sight distance for a crossing maneuver (Case IIIA) is based on the time it takes for a stopped vehicle to clear the intersection and the distance that a vehicle on the major road would travel during the interval. The equation used to calculate this distance is:

$$d = 1.47V(J + t_a) \tag{2}$$

where:

d	=	sight distance along the major highway from the intersection (ft),
V	=	design speed on the major highway (mi/h),
J	=	sum of the perception time and the time required to actuate the clutch or actuate an automatic shift, and
t_a	=	time required to accelerate and traverse the distance S to clear the major highway pavement (s).

The term J represents the time (PRT) necessary for the driver to an perceive adequate gap and to shift gears or actuate an automatic shift.

Sight distances for Cases IIIB and IIIC are calculated on the same principle but include sufficient distance for a vehicle to accelerate to 85 percent of the design speed without being overtaken by a vehicle on the major road. These sight distances are, therefore, substantially longer than those for Case IIIA.

PROJECT OBJECTIVES

One objective of this project was to determine the appropriate PRT values for use in design equations for stopping sight distance, intersection sight distance, and decision sight distance. It evaluated the need for, and utility of, changes to current equations and the potential usefulness of alternative models. The work began with a critical review of current models, human aging and PRT, accident findings, and driver behavior. The greatest part of the project, and a primary objective, was to provide a new set of valid, empirical data on actual driver PRT for older and younger age groups, through the conduct of on-the-road research studies. These findings provided an objective basis for evaluating the need for changes to current parameters or design models. The final objective was to develop recommendations, based on analysis of these findings.

In chapter 2, the key findings of the literature review will be summarized. Following that, the methods and results of the four experiments conducted under this project will be reported (chapter 3). Chapter 4 then considers the implications of the findings for changes to the sight distance equations, while chapter 5 discusses possible alternative models.

CHAPTER 2. LITERATURE REVIEW

The initial phase of this project provided a review of the technical literature and accident findings related to older driver perception-reaction time and sight distance design requirements. This section of the report presents the key findings of the full literature review submitted as an interim report.[14] The review covered four primary topics: age-related changes in PRT; empirical research regarding on-the-road PRT values; accident data findings; and highway design models and equations.

AGE-RELATED CHANGES IN PRT

Age effects in laboratory studies of response time. There is a long tradition of laboratory research on the basic psychomotor processes that are components of PRT. Even for the most simple real-world situations, the response of a person is not a unitary or automatic process. There is a succession of sensory, perceptual, cognitive, and motor processes that bridge the interval from the presentation of a relevant stimulus event to the initiation of an overt response. Furthermore, although various models of driver response might suggest a fixed, strictly serial sequence of processes (e.g., detection, recognition, decision, response selection, response initiation), there is in fact a good deal of parallel activity, preprogramming or biasing of reactions based on expectancies, important effects of experience, planning and behavioral strategies, and attentional set. Thus it is important to keep in mind that even where effects of age have been demonstrated for various distinct psychological processes that underlie PRT, the effect of age on total PRT cannot be viewed as some additive process summing all of these components. Laboratory studies of basic psychomotor processes may help us to understand the causes or the potential magnitude of age effects on more global driving behaviors, but the complexity of actual behavior precludes any simple extrapolation.

Many behaviors slow with advancing age. Numerous reviewers of the literature on aging and response time have described this slowing as a robust and well-established effect that is ubiquitous across a wide range of tasks and research methods.[14,15,16] The laboratory tasks that have been used to investigate the speed of behavior range from simple reaction time tasks (where there is a single, pre-defined event, that must be reacted to with a single, pre-defined response), to more complex choice reaction time tasks (multiple events and responses), to many other tasks such as card sorting, tapping a key, or even handwriting. The finding that these responses take longer with advancing age is quite general, although the magnitude of the age differences can range from a few milliseconds to seconds. A study by Fozard et al., which included both cross-sectional and longitudinal research methods, can be used to illustrate typical findings.[17] They observed an approximately linear increase of about 20 to 25 percent in both simple reaction time and disjunctive reaction time (make a response in reaction to only one of two possible signals) across the age span of 20 to 80 years old. Reaction times were longer for the disjunctive reaction time task than for the simple reaction time task, and the extra time required by older subjects was greater for the disjunctive task. Males responded faster than females, and this difference became more pronounced with age; such an age-by-gender interaction is typical of many studies. For simple reaction time tasks of this sort, the actual response times are on the order of a few hundred milliseconds, ranging from a group mean of roughly 200 ms for 20-year-old males in the simple reaction time task, up to about 500 ms for 90-year-old females in the disjunctive task. Current research studies and theoretical treatments are in general agreement in finding that the slowing with age is primarily due to central processes, rather than peripheral afferent (sensory input) or efferent (nerve output to muscles) processes.

It is not meaningful to talk about a general value for reaction time that is representative of human response across a variety of tasks. The observed times are highly task specific. Furthermore, older people are generally more greatly affected by those task variables that lengthen reaction time; that is, there is an age-by-task interaction. While the reaction time literature is immense and complex, and does not bear detailed review here, some of the variables that contribute to longer reaction times, particularly for older people, can be listed. These include:

- Stimulus attributes: complexity, number, discriminability, etc.
- Response attributes: number of alternatives, response complexity, muscle group involved, opportunity to prepare.
- Stimulus-response compatibility: match in terms of proximity, location, meaning, movement, etc.
- Predictability and preparedness: ability to determine what is likely to occur, or when, or where, or what response may be required.
- Search requirements: range of locations over which target event may occur.
- Distractors: the presence of "noise" events, their number and similarity.
- Memory demands: where previous events determine the appropriate action to take.
- Competing tasks: the presence of simultaneous other activities that must also be carried out.
- Manipulation of visual information: projecting locations based on speed or path, mental rotation of objects, etc.

One way to qualitatively summarize this broad literature is to recognize that as the reaction time task becomes more difficult or complex, older people suffer progressively greater declines in the speed of performance, relative to younger people. Some theorists have even put forward various quantitative embodiments of this general rule, arguing that there is a linear relationship between some measure of task difficulty and the magnitude of the age effect. These laboratory findings suggest that age decrements in an automobile driver's PRT may be sensitive to the details of the driving task. For example, if during low-demand travel on a simple roadway there occurs an obvious event which calls for an unambiguous response, age difference may be relatively small. An illustration might be where a large vehicle pulls onto a low-volume rural roadway directly in front of a driver. In contrast, where a less conspicuous event, requiring a less clear-cut response, occurs while the driver is dealing with competing driving demands, age differences in PRT may be more pronounced. An illustration might be the occurrence of a construction zone lane drop while a driver on a crowded roadway is searching for a route indicator. These examples indicate the need to consider age effects on PRT for specific design situations (e.g., SSD vs. DSD applications), rather than seeking some generic "correction factor" for age that could be applied to all situations.

Search and attention. In typical laboratory studies of reaction time, the subject is anticipating the occurrence of the stimulus event. In real-world driving, the driver must react to numerous events that are not well-anticipated. The mere occurrence of an event does not mean that it falls within the primary (central) visual field, nor that it will be attended to. The process of visual search and the processing of visual information take time. Age differences in visual search processes and in the ability to share and distribute attention can contribute to driver differences in PRT. For this reason it is important to consider both the spatial and temporal aspects of attention.

Considering first the spatial aspects of attention, there are age differences in how drivers search the visual world, the peripheral field in which targets are likely to be detected, and the area of the visual field over which detailed information can be attended to and extracted. Targets detected in the peripheral field are important for guiding subsequent eye movements, to direct focal vision to important events. The size of the visual field shrinks with age.[18] Within the visual field, the ability to attend to cues is not uniform, but decreases with distance from the fovea, and the ability to attend to detail drops more dramatically with distance for older people than for young. The concept of "useful field of view" (UFOV) has been developed to quantify that portion of the visual field which is functional for a given task.[19] The UFOV paradigm is not concerned with the person's ability to merely detect faint targets at the periphery. Rather it concerns people's ability to extract information from complex, suprathreshold targets when attention is focused on some central visual task. Recent research indicates that older adults have a smaller UFOV, that it shrinks faster as the task becomes more demanding (farther displaced target, more demanding central task, more visual noise), and that UFOV measures correlate significantly (with age controlled for) with accident involvement.[20]

Older people also have more difficulty with the time-sharing, or "selective," aspects of attention. The brain cannot fully deal with all of the information impinging on the person at a given moment, and so cognitive activity has a "selective" aspect to it. There are two general types of attentional aspects which are of interest here. While the terminology varies from author to author, these can be characterized as (a) "selective attention," which deals with directing attention to certain information at the expense of other, less relevant, information; and (b) "divided attention," which deals with monitoring two or more sources of simultaneous relevant information. Although the literature findings are complex, the general evidence is for age-related declines in both selective and divided attention capabilities. A recent review has identified three types of selective attention errors -- omissions, intrusions, and switching -- all of which are age-related, and which also correlate, at least moderately, with driving accident rates. Divided attention abilities also decline with age, but the evidence relating this capability to accident rates is more ambiguous.[21]

In summary, a variety of declines in attentional ability have the potential to increase older driver PRT, due to diminished ability to attend to targets within a given field of view, greater difficulty in restricting attention to relevant cues, less ability to switch attention when the need arises, and reduced ability to attend to more than one thing at a time. Driving situations that emphasize the need for such attentional skills might be particularly likely to result in slower response times for older drivers.

Laboratory simulation of driver reaction time. There have been a number of laboratory studies that simulated some aspect of the driving task and examined reaction times for different driver groups. Most of these "simulations" have not really tried to simulate the driving *per se*, but rather just looked at the time it takes someone sitting in a car-like environment to step on a brake pedal, in response to some simple signal (e.g., a red light display). Across a variety of these brake pedal reaction time experiments, the finding has been a typical mean time of about a half-second.[14] Usually a significant effect of age has been obtained, with "older" subjects (variously defined) typically having mean response times of around 0.6 or 0.7 s; age-by-gender interactions typical of other reaction time procedures, with older females slowing more than older males, have also been reported.[22] Among older people, laboratory brake reaction time has been related to the amount of driving a person currently does: older people who drove daily had a mean reaction time of 0.7 s, infrequent drivers had a mean of 0.84 s, and non-drivers a mean of 1.33 s.[23] In addition to laboratory studies of simple brake reaction time, there have also been choice reaction time experiments (e.g., step on brake pedal in response to red light, step on accelerator in response to green light). These studies, too, have typically shown somewhat longer reaction times, and in some cases more errors, for older subjects.[25]

Two studies of decisionmaking time at intersections used video projections of approaches to and drives through an intersection, and looked at foot pedal responses to determine when drivers reached their decisions about appropriate maneuvers.[26,27] Both studies found a significant effect of age cn decision time. Unlike the brake reaction time studies, subjects in these experiments were not trying to respond as quickly as possible, but to "drive" normally. The observed differences between age groups (about 2 s) were much larger than seen in the brake reaction time experiments; whether this is due to the fact that responding was not forced to be fast, or to differences in "driving style," or some other methodological feature is not known.

In summary, brake reaction time experiments carried out in driving consoles typically (but not universally), have found older subjects to have longer brake reaction times. However, the absolute values of the times observed for all age groups are much faster than those actually observed in on-the-road driving, so that it is difficult to project the implications of these findings for actual driving.

PRT ON THE ROAD

There have been various attempts to measure on-the-road PRT for SSD, ISD, and DSD situations. Only a few have considered age differences in PRT. The primary on-road findings will be summarized here. These are data obtained from drivers on actual roadways, as opposed to more artificial test track situations. The findings summarized below primarily are based on research that did not include any consideration of the older driver. Those few studies that did explicitly consider older drivers are discussed at the end of this section.

By far the most research has concerned braking PRT for the SSD situation. One critical variable is whether the driver/subject is anticipating the occurrence of the event that requires the brake response. In some cases this is an arbitrary signal (e.g., brake whenever a sound comes on), and in other cases it may be a more realistic roadway condition (e.g., object in the roadway), but the subject is aware that such events may occur. For experiments in which the subject is alerted to the possibility of the need to brake, response times are briefer than in studies with unalerted subjects. In one of the most widely cited studies using alerted subjects, a median time of 0.66 s was obtained, with a mean of about 0.75 s, a 95th percentile of about 1.2 s, and a range of about 0.3 to 2.0 s.[28] These results are fairly typical of the literature, with mean values in the range of one-half to three-fourths of a second, and upper percentile values well below two seconds.

When drivers are unalerted, that is, have no expectation that a braking event will occur, the observed PRT are longer. Findings from unalerted drivers will obviously be more pertinent to highway design and safety issues than data from alerted subjects who anticipate the need to brake. Studies of unalerted drivers have measured PRT in response to a lead vehicle's brake lamps, objects or vehicles in the road ahead, or events such as a parked car door opening or a bicyclist emerging. (See references 29,30,31,32,33,34,35,36.) While these varying "hazards" and experimental conditions naturally lead to some differences in the findings, there has been general agreement in finding an average PRT for the unalerted driver somewhere in the range of 1.0 to 1.5 s. The upper percentile ranges are less well described in most reports, and probably less consistent between experiments; however, the upper percentile ranges can approach 2.0 s, with some individual cases beyond 2.0 s.

Very little research measuring on-the-road PRT for ISD and DSD situations was uncovered. The major study for ISD was conducted by Hostetter et al., and addressed both Case II (Yield-controlled) and Case III (Stop-controlled) intersections.[13] For Case II intersections, PRT was defined as the interval from the first possible detection of the intersection/sign to the moment the accelerator pedal was released or the brake pedal activated. Unfortunately, for various reasons these data are not helpful for deriving useful estimates of driver PRT. Generally the sight distances approaching the intersections were quite long, so that pedal responses probably reflected driving style on approach, rather than any reaction time. The PRT observed at various sites were strongly related to the available sight distance. Overall, the mean PRT observed was 22 s, but for the site with least sight distance, it was only about 5 s. For the Case III intersections, this study evaluated the PRT required for a driver, stopped at the stop sign, to make the decision to proceed with the maneuver (defined by pressing the accelerator). A major difficulty in defining Case III PRT is in determining what event most appropriately defines the beginning of the PRT interval. Hostetter et al. actually used three separate definitions (when vehicle came to stop; first head movement following stop; final head movement in direction opposite of turn). None of these definitions took into account the fact that drivers frequently begin scanning the crossroad as they begin to approach the stop. The most conservative PRT measure (defined from the point of stopping) yielded mean PRT of 2.21 s for 4-way stops and 2.84 s for T-intersections. The least conservative measure (and the one favored by Hostetter et al.) yielded means of 1.60 and 1.76 s. Corresponding 85th percentile values were 2.72 and 3.11 s for the first definition, and 2.46 and 2.46 s for the other.[13]

For DSD, the only on-road observational study of PRT appears to be the small "validation study" of McGee et al.[11] In this experiment, drivers traveled a route that included eight DSD situations, including lane drop exits, lane splits, lane reductions, and left turn lanes.

As the subject, driving in the right lane, encountered each site, he or she (1) pressed the (deactivated) horn to record the point at which the driver saw the situation; (2) verbally explained what was seen; (3) initiated the appropriate path or speed change (as recorded by the experimenter); and (4) completed the maneuver (judged by the experimenter). By relating the point at which the situation was recognized to the point at which a key physical feature was first in direct view, the detection/recognition time could be computed. The interval from the point of recognition to the initiation of the path or speed maneuver defined a decision/response phase. These two times, taken together, defined a PRT (from the point of potential detection to the initiation of the maneuver). For the various sites, the detection/recognition phase ranged from 1.78 to 15.07 s (mean of 5.7 s), and the decision/response phase ranged from 2.71 to 13.69 s (mean of 4.8 s). There were not only wide differences between sites, but between individual drivers as well. A variety of methodological issues cloud the findings, and the authors cautioned against acceptance of some of the longer values.

Overall, then, a variety of studies suggest that the mean PRT for unalerted drivers in a SSD situation is on the order of 1.0 to 1.5 s, with upper percentile values being less than 2.0 s. Comparable on-the-road data for ISD and DSD situations is minimal, and a variety of methodological issues make interpretation of the findings difficult.

A few of the on-road studies were able to provide comparisons of the PRT of older and younger subjects. In a major study of braking PRT, minimal differences were seen between older (mean unspecified; range of 60 to 84) and younger (18 to 40) subjects.[33] Although data were not tabled (and statistical significance not reported), based on cumulative percentile plots, the median PRT was actually slightly faster (perhaps 0.05 s) for the older group. At the 85th percentile, the two age groups again appeared to be within about 0.05 s of each other. In an experiment concerning braking to a lead vehicle's actions, the PRT of the older group (mean age of 66) was slightly, but not significantly, slower than that of the younger group (mean age of 30).[24] In their studies of Case II and Case III intersections, Hostetter et al., found age differences to be small, inconsistent, and of no "practical" effect.[13] In summary, then, the few on-the-road studies that have compared the PRT of older and younger subjects have not found any evidence of longer PRT for older drivers.

ACCIDENT FINDINGS

<u>Research Findings on Safety Effects of Sight Distance</u>. There is evidence that insufficient SSD, ISD, and DSD all can contribute to higher accident rates. Beyond this simple statement, however, the relationship between each type of sight distance and accidents has proven to be complex and difficult to quantify. For example, when pairs of sites differing in available SSD, but matched for other attributes, were compared, the limited SSD sites were found to experience significantly more accidents.[33] This helps confirm the safety detriment of limited SSD, but does little to quantify the problem. Good descriptions of research studies, findings, and limitations may be found for SSD, ISD, and DSD. (See references 37,38,39,40,41,42.) Some of the primary difficulties in being able to draw refined conclusions or quantitative relationships from existing accident data include the following: accident reports typically do not provide reliable and/or quantitative information on sight

distance; accident records and State roadway geometric data bases lack enough precision to accurately locate the accident with respect to sight distance limitations; limited sight distance is often confounded with other geometric features (e.g., sharp curvature) or operational characteristics; it is often difficult to determine whether a particular accident at a site with limited sight distance was attributable to the sight distance restriction; it is difficult to match and control sites for factors other than sight distance, and the number of suitable comparison sites may be very limited; accident frequencies at individual sites are often too low to allow statistically meaningful comparisons. To summarize, it is clear from the literature that deficiencies in SSD, ISD, or DSD can lead to increased accidents, at least under certain conditions, but it is difficult to derive more quantitative relationships from the current findings.

General Features of Older Driver Accident Experience. Given the limitations to the general literature on sight distance and accidents, it is not surprising to find that there are little data specifically addressing the accident involvement of older drivers as a function of sight distance variables. However, general features of the older driver accident experience may help indicate who the "older" driver is, and how typical older driver accidents may relate to sight distance concerns.

The per-mile accident involvement rate remains relatively stable from about age 30 through middle age, and then begins to accelerate with advancing age. This general pattern has been replicated in numerous studies. However, the age at which this acceleration begins to occur, and the magnitude of the increase, very much depend on the accident measure (fatal accidents, injury accidents, police-reported accidents, all accidents), the exposure measure (per capita, per licensed driver, per mile driven, induced exposure rates), and the type of accident considered (e.g., all collisions, single or multivehicle collisions, intersection-related collisions, etc.). The shape of the age function may also be different for male and female drivers. Thus it is quite difficult make any general statement about the age at which the "older driver" problem begins to emerge or how critical it is at any given age. The difficulties of providing comparable exposure measures for older and younger drivers further complicates the issue, given that the type of driving done by older drivers is different from that of younger people in many respects. Furthermore, the greater vulnerability of older drivers (i.e., the greater likelihood of injury or death for a given crash severity) can exaggerate the shape of these age functions.[6] While all of these considerations preclude any simplistic statement about age and accident rate, a few important generalizations are supportable: (1) there is relatively little evidence of a meaningful degree of over-involvement in accidents prior to the mid-sixties; (2) substantial over-involvement is usually evident by the early seventies; (3) per-mile accident involvement rates continue to accelerate with increasing age, through the sixties, seventies, and eighties.

Based on the range of older driver accident studies, there are some implications to be drawn for research on highway design criteria for older drivers. Unless data for the specific accident type of interest indicates otherwise, the definition of an "older" driver probably should not include those younger than age 65. Many basic human performance capabilities show some measurable decline well before this (e.g., visual acuity, reaction time), but these are not expressed in noticeably greater accident involvement rates until the mid-sixties. Drivers between 65 and 70 may not show as dramatic an increase in accident rates as those over 70, but they are important to consider because there is typically some indication of elevated accident rates, coupled with the fact that drivers of this age drive many more per capita miles than those over age 70. Finally, those over age 70 should be considered in sufficient degree, since accident consequences become more exaggerated beyond this age. Thus, based on both the emergence of increased accident rates and the number of driving miles contributed, it appears reasonable to define the older driver as 65 or older; but it is also apparent that any consideration of the older driver must also include meaningful numbers of those over the age of 70, where the problems become more pronounced. Based on these considerations, the research studies conducted under this project (chapter 3) explicitly defined two older driver groups, one aged 65 to 69, the other 70 and older.

The general literature on older drivers and accidents was also reviewed to determine whether the types or locations of accidents that typify older drivers could be related to changes in PRT. The conclusions were rather ambiguous, in part because PRT is potentially an important factor in so many types of accidents. Older drivers are particularly overrepresented in multiple-vehicle, intersection-related accidents, which could be interpreted to reflect slow detection of and reaction to other vehicles, or slow decision times for intersection-related maneuvers. On the other hand, the relatively minor effects of age on rear-end collisions and struck-object (single vehicle) collisions suggests that older drivers are not failing to react in time, at least in some situations. Older driver accident over-involvement is not as great on Interstate highways as on other roads. This might reflect higher roadway design standards which minimize the demands for rapid PRT; but the higher speeds on Interstate highways might suggest a greater need for rapid PRT. After reviewing a wide variety of accident studies, the conclusion was that it is simply too speculative to attempt to draw inferences about the effects of slower PRT as a factor in older driver accidents, based on typical accident types. Thus while virtually any model of driving behavior can analytically derive the importance of rapid decision and motor processes, the existing accident literature provides little evidence, direct or indirect, regarding the role of age differences in PRT on the patterns of accident experience.

HIGHWAY DESIGN MODELS AND EQUATIONS

This section presents an evaluation of the existing highway design models and their adequacy to meet the needs of older drivers. This review focuses on the issues that relate specifically to perception reaction time (PRT). Clearly, though, this issue is sensitive to a great number of factors and abilities, and the review must be wide ranging.

Current Models and Their Adequacy. All of the sight distance standards are developed based on the same model. A selected PRT is multiplied by the appropriate design speed, and a maneuver component (e.g., stopping distance) is added to arrive at the sight distance. PRT values have been based primarily on a sequential information processing model which assumes that the driver performs certain tasks in a serial process of detection, perception, decision, and response.

Human factors researchers recognize that these tasks are not performed in sequence, but in driving behavior research it is nearly impossible to identify the overlaps. This is an important point for older drivers because while they may take longer to perform certain subtasks in certain situations, they probably compensate by being quicker in other subtasks or take compensatory action (such as driving more slowly, keeping longer headways, etc.)

Sight distance standards, and the models and parameters they are based upon, have been evaluated by numerous researchers over time. For example, McGee et al. conducted a thorough review of how driver characteristics are considered in highway design and operation standards.[2] The study included the identification of driver characteristics and their specification, a sensitivity analysis to determine how the standard values change as a function of driver characteristic, and a critique of the model or procedure employed. "Adequacy" of the model was judged by how well it considered the requirements of the driver as documented in available research. [The true test of "adequacy" is whether or not the designs that employ the standard provide a safe and efficient driving environment for the motorist. This requires establishing a good relationship of safety (accident probability) to the design standard, in this case available sight distance.] In the judgment of the researchers, the models for some of the sight distance standards were inadequate. Specifically, they criticized the Case I intersection sight distance standard for not allowing a margin of safety, and offered an alternative approach. They also were critical of the Case II ISD standard, stating that the standard will sometimes place the driver in a situation where a speed change must be made to avoid a collision but where sufficient stopping distance is not available. Their evaluation also uncovered a flaw in the sight distance formulation for the sight triangle at railroad crossings; this error was corrected and the recommended modified formula was included in the 1984 AASHTO Green Book.[12] Finally, they reviewed the adequacy of the object height for various sight distances and suggested modifications and further considerations for revisions.

More recent evaluations of various sight distance models are documented in several papers in *Transportation Research Record 1208*, which is a compendium of presentations from two conference sessions at the 1989 Annual Meeting of TRB.[43] Some of the deficiencies and suggested modifications to existing models noted by several authors are:

- Hall and Turner, Urbanik et al., as well as McGee et al. in an earlier paper, question the validity of specifying an object height 6 in (152 mm) high for several reasons. This issue may be particularly relevant for older drivers because of their vision limitations. Seeing a 6-in (152-mm) high object at the long distances required for high design speeds may be a problem for older drivers. When illumination of the object is by headlights, it becomes impossible at high speeds even for younger drivers.[38,44,2]

- Hall and Turner question whether the existing SSD model properly portrays realistic hazards and considers realistic conditions. Driver behavior models always tend to structure and quantify motorists' information processing and performance in simplistic terms.[38]

- Neuman argues the point that drivers respond differently for different situations and highway types and, therefore, the SSD standards should reflect these differences. He offers possible adjustments to various parameters, including the PRT values that range from 4.0 s for a low-volume road to 7.0 s for an urban freeway. Also, SSD design values should be separately derived for major reconstruction versus new construction. The quest for cost-effective design standards underlies this contention.[45]

- Urbanik et al., in an effort to evaluate the safety effects of limited sight distance on crest vertical curves (one of the key applications of sight distance and PRT) concluded: "The relationship between available sight distance and crest vertical curves on two-lane roadways and accidents is difficult to quantify even when a large database exists." The AASHTO SSD alone is not a good indicator of accident rates on two-lane roads. Hence, designing projects based solely on the SSD model will not result in cost-effective projects.[44]

- Glennon performed a critical review of the SSD. He concluded that "Alignment changes are normally cost effective on highways that have (a) very high traffic volumes, and (b) major hazards that are hidden by a sight obstruction. SSD on horizontal curves may be a particular problem. Cornering forces on tires consume a portion of the friction force that might otherwise be used for deceleration. In addition, large trucks require longer SSD than cars. For vertical curves, the truck driver's increased eye-height offsets the required additional stopping distance; this advantage is not available for horizontal curves."[46]

<u>Currently Used Values and Their Adequacy</u>. Most researchers have confirmed the adequacy of currently used values of PRT for SSD (2.5 s) for the general driving population as specified in current AASHTO policy. These values have come under scrutiny on several occasions, most recently by Olson et al. who suggested that 2.5 s was adequate for older drivers, since no difference was found between the age groups.[33] Even though a PRT of 2.5 s was found adequate for the older subjects in the experiment, this conclusion may have resulted from a number of artifactual causes and included the following: (a) the tests were performed during daylight and under good visibility conditions; (b) the older drivers who participated in this study may have been abnormally alert because of their mental readiness for the test; and, (c) the test may not have represented more complex driving situations where older drivers are more likely to take longer cognitive processing time than younger drivers. In addition, driver studies are generally based on samples which may have a certain degree of "volunteer bias" (i.e., due to the fact that participation of individuals in driver studies is dependent on their consent, such samples can not be considered random).

Neuman questioned a PRT of 2.5 s in certain situations.[45] He argued that depending on the physical state of the driver (i.e., either alert or fatigued), the complexity of the driving task, and the location and functional class of the highway, PRT values could vary from 1.5 s to 5.0 s.

PRT values for DSD, though dependent on road type and maneuver, are substantially higher than those used for SSD. The AASHTO policy of 1990 provides DSD values for five specific situations.[10] There is no explanation as to what PRT values were used for computing these sight distances. However, the AASHTO policy of 1984 gives DSD and PRT values for a lane change maneuver.[12] PRT values used for computing these DSD vary from 5.7 s on a rural roadway at 30 mi/h (48 km/h) to 10.0 s on an urban freeway at

70 mi/h (113 km/h). It is interesting to note that PRT values increase as a function of vehicle speed; the empirical basis for this assumption is not clear.

For situations involving more complex decision making, though, it is generally recognized that sight distances longer than the SSD need to be provided. The main reason States have been reluctant to adopt longer DSD is the considerable additional cost associated with the provision of longer vertical and horizontal curves. McGee, in an effort to evaluate the effectiveness of and compliance with current DSD standards (1984 AASHTO policy only), confirms that DSD criteria "have not been adopted because the costs of the longer distances required have not been justified."[41,12] There is no evidence in the literature as to the adequacy of these values to accommodate the older driver. However, because older adults require longer cognitive processing time and show slower reactions for many tasks, it is likely that older drivers will require longer PRT for DSD applications.

The PRT value for the three Case III intersection sight distances is assumed at 2.0 s. For Case IIIA, the AASHTO policy states that while "most drivers may require only a fraction of a second, a value of J [term representing PRT] should be used in design to represent the time taken by the slower driver." Some researchers have suggested a value of PRT as low as 0.5 s. However, these assumptions need to be carefully reexamined to verify the provision of adequate PRT to meet the needs of the older driver.

One last question relates to the proportion of the population that is to be covered by the design standards. By implementing standards based on the 85th or 95th percentile driver, a portion of the population is excluded. The characteristics of the excluded drivers is unknown and use of such criterion may be resulting in inadequate design for a substantial portion of older drivers.

CHAPTER 3. RESEARCH STUDIES

OVERVIEW OF EXPERIMENTS

<u>Set of experiments</u>. A set of four experiments was conducted, which together addressed three PRT situations: Case III intersection PRT; stopping sight distance PRT; and decision sight distance PRT. One experiment did not directly measure PRT, but rather gap/lag acceptance; this was included as a complement to the experiment on Case III intersection PRT.

The Case III intersection PRT experiment is discussed first. In this experiment, subjects drove their vehicles over an extended route, including a number of Stop-controlled intersections. The experimental procedures were designed so that the initiation of visual search could be well defined, permitting measurement of the PRT (from initiation of search, after stopping, to initiation of forward vehicle movement). The experiment included a variety of intersection characteristics, and left turn, right turn, and crossing vehicle maneuvers.

The stopping sight distance PRT experiment is discussed second. In this experiment, subjects were driving their cars along a route, and did not know that an event requiring rapid braking would occur. At one point along the route, protected from other traffic, a crash barrel rolled from behind brush on a berm, and onto the edge of the roadway. The driver's PRT was measured from the moment the barrel came into the driver's view until the driver stepped on the brake.

The decision sight distance experiment is discussed third. In this experiment, subjects drove their vehicles along an extended route that included both freeway and arterial sections. At various sites, lane change maneuvers were required by roadway features that were appropriate to the decision sight distance model. Drivers verbalized when the first noted the necessity of changing lanes; they also verbally indicated the cue which informed them of the need to make the maneuver. PRT was measured from the point where the cue first became visible, to the moment the driver verbalized the need to change lanes.

The gap/lag acceptance experiment is discussed fourth. This experiment differed from the others in that subjects were not actually driving. Rather, they viewed traffic from a vehicle on the roadside, and made decisions about when it would be safe to make various maneuvers. The findings were presented in terms of the probability of accepting gaps or lags of a given duration. These findings serve as a point of comparison with the PRT data from the Case III intersection experiment.

Together, these experiments provided realistic, on-the-road measurement of PRT for drivers of different ages, and for different PRT situations. The method and primary findings of each experiment is described in the sections that follow.

<u>Common features of the experiments</u>. The experiments included a number of common features that will be discussed here. First, all experiments involved the comparison of three

age groups: 20 to 40 years old, 65 to 69 years old, and 70 or older. Each age group contained approximately equal numbers of men and women.

The philosophy underlying the experiments was that measurements of PRT must be valid in an absolute sense. That is, it was not enough to simply determine whether or not the age groups differed in PRT. The actual values observed were critical, because these were to be related to design equations. For this reason, the three PRT experiments all measured drivers who were operating their own vehicles, and on actual roadways, not test tracks. The drivers were not informed that their response times were being measured; in the intersection and stopping sight distance experiments, the subjects actually thought the experiment had another purpose entirely. The procedures were carefully devised so that the subject had the appropriate "mental set" while driving, and was behaving in a normal manner. In all cases, the experimenter was present in the rear seat of the vehicle, and acted unobtrusively. Also since the presence of a passenger might influence driver behavior, one function of the extended routes was to adapt the driver, and in fact, subjects appeared generally relaxed and at ease.

The experiments all used video-based data collection systems, although the details varied among experiments. The video recordings allowed determination of roadway locations, traffic events, and driver actions. Because the video system was used as part of the PRT measurement system, the precision of measurement was related to the time-base of the video equipment. Since the frame rate was 30/s, the level of precision is about 33 ms. This degree of precision is certainly adequate for the measurement meaningful differences in on-the-road driver response times.

In analyzing the findings, the interest was not simply with comparing central tendencies among age groups; the distribution of times was of major interest. Because highway design and operational practices cannot just match the characteristics of the "average" driver, information must be presented on the performance of upper percentile subjects as well.

Recruiting of research subjects. All subjects were recruited in the greater Washington, DC, area, primarily from suburban Maryland (intersection, stopping sight distance, and gap/lag acceptance experiments) and Northern Virginia (decision sight distance). In order to participate, subjects were required to have a current license, and have access to their own personal vehicle. Subjects were paid for their participation.

One concern in research studies using older drivers is the bias caused by self-selection. Because participation is voluntary, the more adventuresome and capable will be more likely to volunteer, and the least confident will be less likely to volunteer. Efforts can be made to minimize this bias, although it probably cannot be eliminated. The recruiting procedures of the experiments were designed to secure a broadly representative range of older drivers. To minimize the selection bias toward more capable older drivers, experienced recruiters worked through senior centers, churches, retirement communities, and so forth. Rather than placing initiative on the subject to volunteer, as much as possible we worked with directors of the institutions to help identify and approach individuals with a wide range of capabilities, and to provide social support and incentive for taking part. Although there can be no claim that the sample was representative, and while it is likely that those at the extreme lowest limits of ability and confidence tended to exclude themselves, the older group did appear to provide a broadly suitable range, and certainly included many individuals who would have been unlikely to participate without more active recruiting strategies.

CASE III INTERSECTION PRRT

<u>Method</u>. This experiment addressed the situation of a motorist stopped on a minor road, attempting to enter, or cross, a major road. The driver must have sufficient visibility along the major road to confirm that there is enough time to complete the maneuver before any oncoming vehicle reaches the intersection. The model for defining the required sight distance for a crossing maneuver is $d = 1.47V(J + t_a)$. The J term is the PRT component, and represents the time to perceive the intersection and actuate the clutch or automatic shift. The current design value is 2.0 s. The t_a term is the time required to accelerate and clear the major highway pavement (for a crossing maneuver) or to accelerate and reach 85 percent of the major road design speed (for turning maneuver).

The primary purpose of this experiment was to compare the PRT of older drivers with those of younger drivers and with the 2.0 s design value. The study also recorded the maneuver time. One of the difficulties in the on-road study of intersection PRT is that of determining when visual search begins and ends. Drivers may begin scanning the major roadway as they approach the stop sign, and continue to monitor their decision even while they begin executing the maneuver. Thus actual behavior does not always fit the design model well (stop-search-proceed). In the experiment, drivers were given a task to do once stopped at the intersection, which broke visual search. The moment at which search began again was controlled and recorded. Thus a clear "start" time for search was defined; the initiation of forward vehicle movement defined the end of the PRT, and the beginning of the maneuver. The completion of the maneuver was defined when the vehicle reached a designated point on the roadway.

For this experiment, subjects drove their own cars along a route designated by the experimenter. The car was fitted with a data collection system that was comprised of four video cameras, a videocassette recorder, computer, input/output switches from the subject and the experimenter, monitor and keyboard for the experimenter, and power supply. Three of the video cameras were roof-mounted, providing a 180-degree view forward of the vehicle; the fourth camera was an interior microcamera that recorded the head and torso of the driver. All four camera images were combined on a single recording through use of a quad splitter.

The research subjects thought that the purpose of the experiment was to study people's judgments about road quality and how this related to aspects of driving. They did not know that the study concerned intersections or that their response times were being measured. They thought the judgments of road quality that they were required to make were the data of interest, when in fact these were used only as a means of controlling visual search at intersections. When the subject reached an intersection at which PRT data were to be recorded, he or she was told to make ratings of the quality of the best and the worst sections of the roadway segment just traveled. The subject had to look down at a key pad in order to make these ratings. The subject was instructed not to look up until the experimenter activated an "OK to Proceed" lamp mounted on the key pad. The subject acknowledged seeing the "OK" lamp by pushing a "ready" button, then looking up and proceeding as normal.. The response to the ready button defined the start of the visual search process, and the initiation of forward travel defined the end of the PRT. This definition of PRT parallels the definitions of the J term in the AASHTO equation: "sum of the perception time and the time required to actuate the clutch or actuate on automatic shift." This experiment also measured a "maneuver time," which was the time from the initiation of movement to the time at which the vehicle reached some criterion point on the roads. For crossing maneuvers, and the left turns on divided roadways, this definition parallels the AASHTO definition of t_a: "time required to accelerate and travels the distance S to clear the major highway pavement." For turning maneuvers, the criterion for completion of the maneuver differs from AASHTO. AASHTO defines t_a as the time required to accelerate to 85 percent of the design speed of the major road. In the present experiment, there was no measure of vehicle speed, and the criterion point was defined by the location where the vehicie path was oriented to be parallel with the roadway. Although the preliminary interest in this research was with PRT, it was considered useful to have some comparative data for the age groups for making the maneuver itself. Therefore, the maneuver time data should be treated as relative, and not in terms of its absolute match to AASHTO values.

The route included 14 data collection sites (11 for night sessions) for intersection sight distance. A few minutes after the final site, the subject encountered the site for the stopping sight distance PRT experiment, described later. They then returned to the initial staging site, with the entire route encompassing 56 mi (90 km). The intersection sites varied in terms of the primary roadway features (posted speed, number of lanes, divided/undivided, right angle/oblique, etc.) and in the maneuver required of the driver (turn left, turn right, cross through). The number of participating subjects in each age group is shown in table 3. Fewer night sessions were run, since that portion of the procedure was terminated when it became apparent that PRT were longer in the daytime for all age groups.

Table 3. Number of subjects: Case III intersection experiment.

	20-40 Years Old	65-69 Years Old	70+ Years Old	TOTAL
Day	F 14	F 14	F 11	F 39
	M 11	M 13	M 18	M 42
Night	F 5	F 4	F 0	F 9
	M 3	M 4	M 5	M 12
TOTAL	33	35	34	102

Results. Day vs. night. Figure 1 (panels A, B, and C) shows the effect of light condition (day vs. night) on PRT, maneuver time, and total time (PRT + maneuver time). The figures show aggregated data, collapsed over sites, maneuvers, and subject variables. The graphs are cumulative percentage plots, with day and night functions shown separately. The X-axis shows time, and the height of the function at a given time corresponds to the proportion of subjects responding as fast or faster than that time. The vertical bars are drawn through the median and 85th-percentile points for each function. The median and 85th percentile PRT (panel A) were about 0.3 s longer in daytime, maneuver times (panel B) were also slightly longer in day, and the total time (panel C) was about 0.3 to 0.4 s longer. The finding of longer times under day conditions continues to hold when the data are disaggregated by age group or site characteristics. However, since there were fewer women in the older age group, it was possible that the briefer times at night were reflecting this confound. Therefore, analogous figures were generated for male subjects only (figure 2, panels A, B, and C). Again, PRT were longer in the daytime. Maneuver and total times were more similar. In terms of absolute value, the median daytime PRT was approximately 1.3 s. The 85th-percentile daytime PRT was approximately 2.0 s, the value used in current AASHTO equations.

Because it is the longer daytime PRT values that will drive any need to reconsider the corresponding parameter in the design equation, nighttime data collection was terminated once the difference became evident. The rest of the analysis that follows is confined to daytime data.

Age and gender effects. Figure 3 (panels A, B, and C) shows cumulative percentage plots for the three age groups. Again, these data are aggregated over all sites and maneuvers. These data show that the younger age group took somewhat longer to initiate movement (PRT) than the older groups. The difference is on the order of 0.2 s. Maneuver times are slightly faster for the young group, with little difference in the total times. Figure 4 (panels A, B, and C) shows group mean values for each measure. Separate points are shown for males and females within each age group. Table 4 presents the results of analyses of variance based on these data. The analyses were based on a two-factor (age and gender) independent groups factorial design. For each subject, a mean score was derived based on all data for that subject. The analyses of variance were based on these individual means; separate analyses was conducted for PRT, maneuver time, and total time. For PRT, the main effects of both age and gender were statistically significant, as was their interaction. For maneuver time and total time, neither main effect was significant, but the interactions of age and gender were statistically significant. The interaction effects in all these cases were related to the slower performance of females, compared to males, in the oldest age group. However, it should be noted that the relatively slower PRT of older females still were comparable to the PRT of younger subjects in this experiment.

Although the older subjects did not take longer than the younger subjects to initiate forward movement, it is none-the-less possible that they were taking more time to visually evaluate the situation. Although the design equation for SSD is based on a sequential model, in which the driver searches, makes a decision, and then proceeds, drivers will actually continue to scan the intersection after they have initiated forward movement. It is therefore possible that

A

B

C

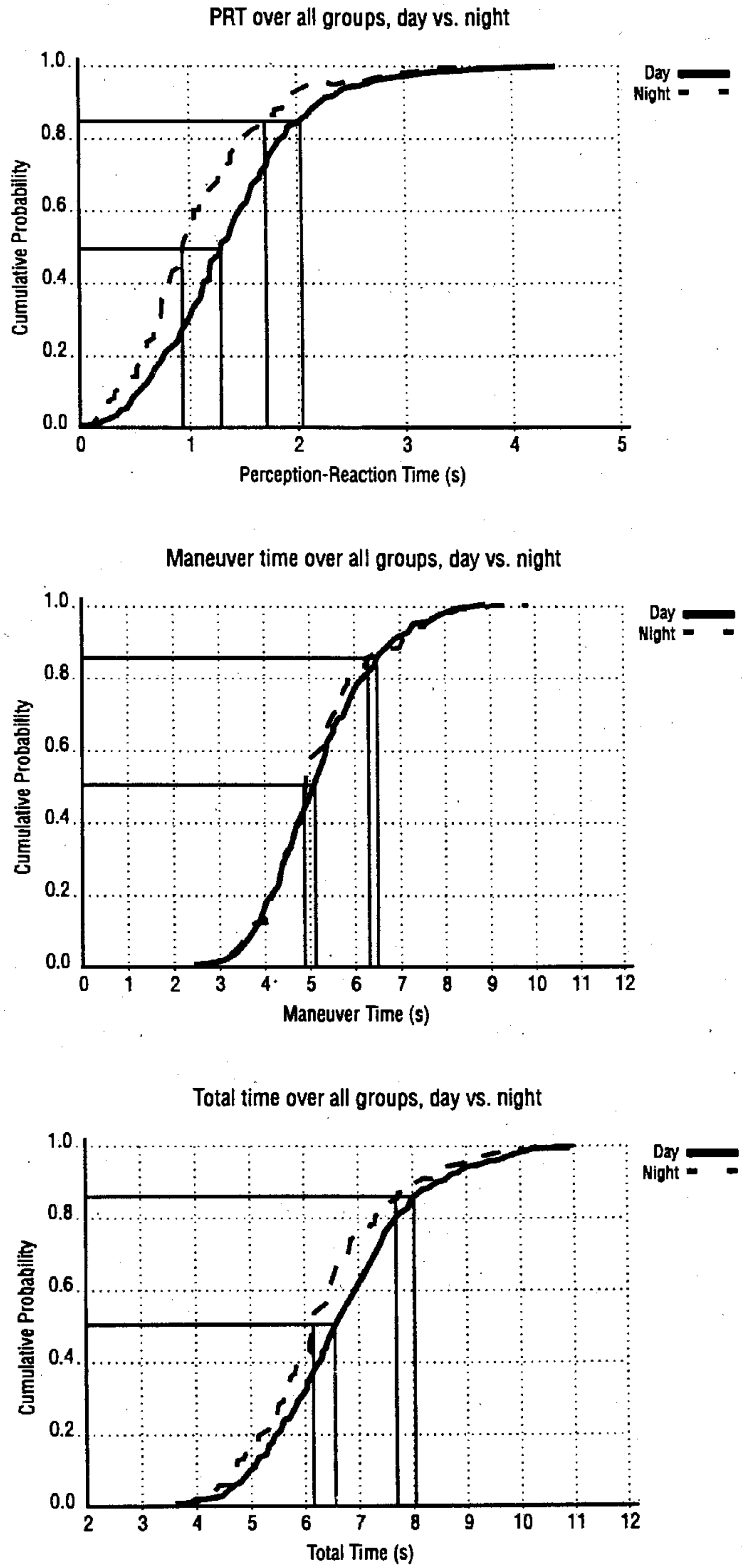


Figure 1. Cumulative probability for all groups, day vs. night.
(50th- and 85th-percentile points included in the figure.)

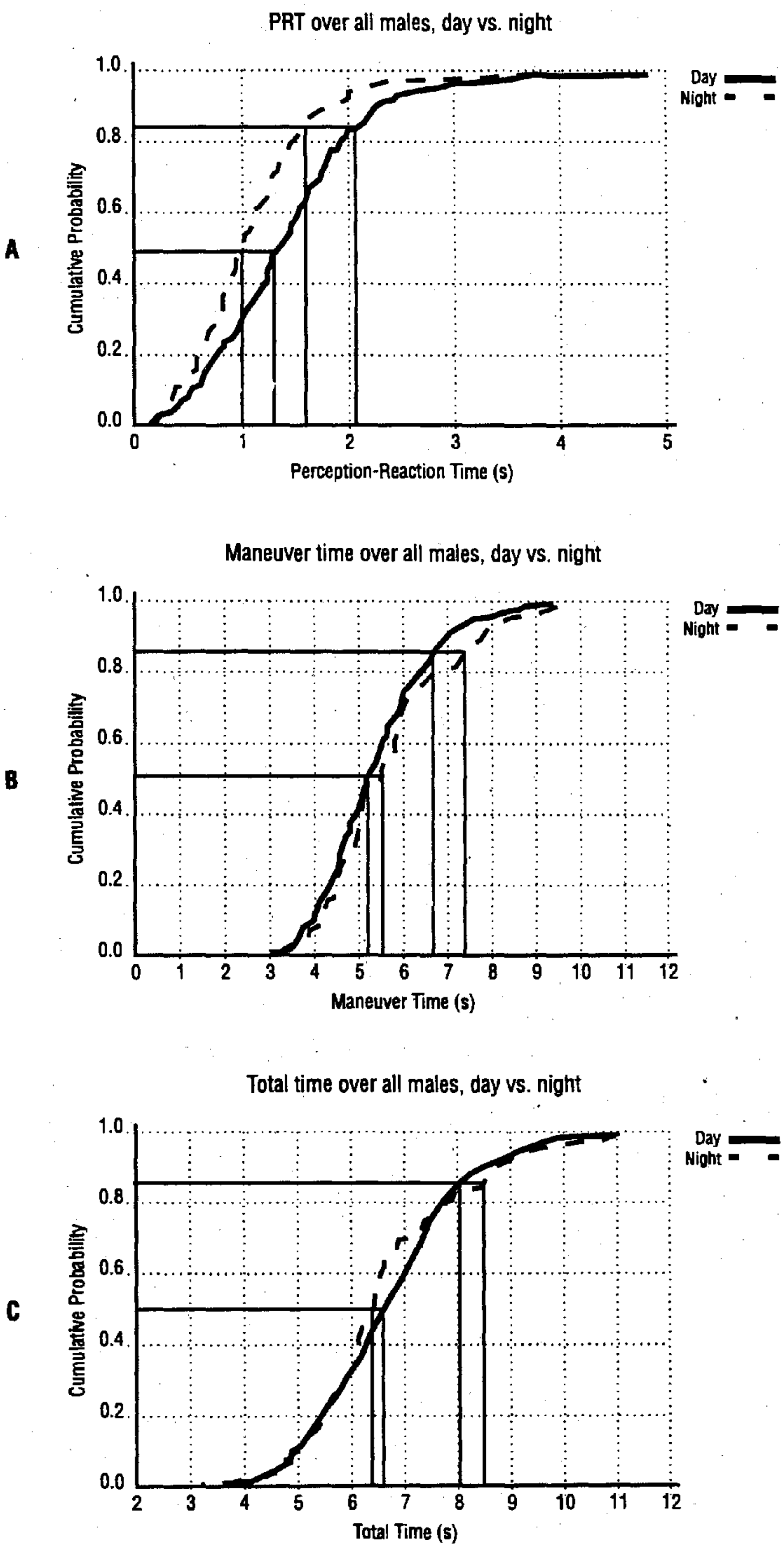


Figure 2. Cumulative probability for all males, day vs. night. (50th- and 85th-percentile points included in the figure.)

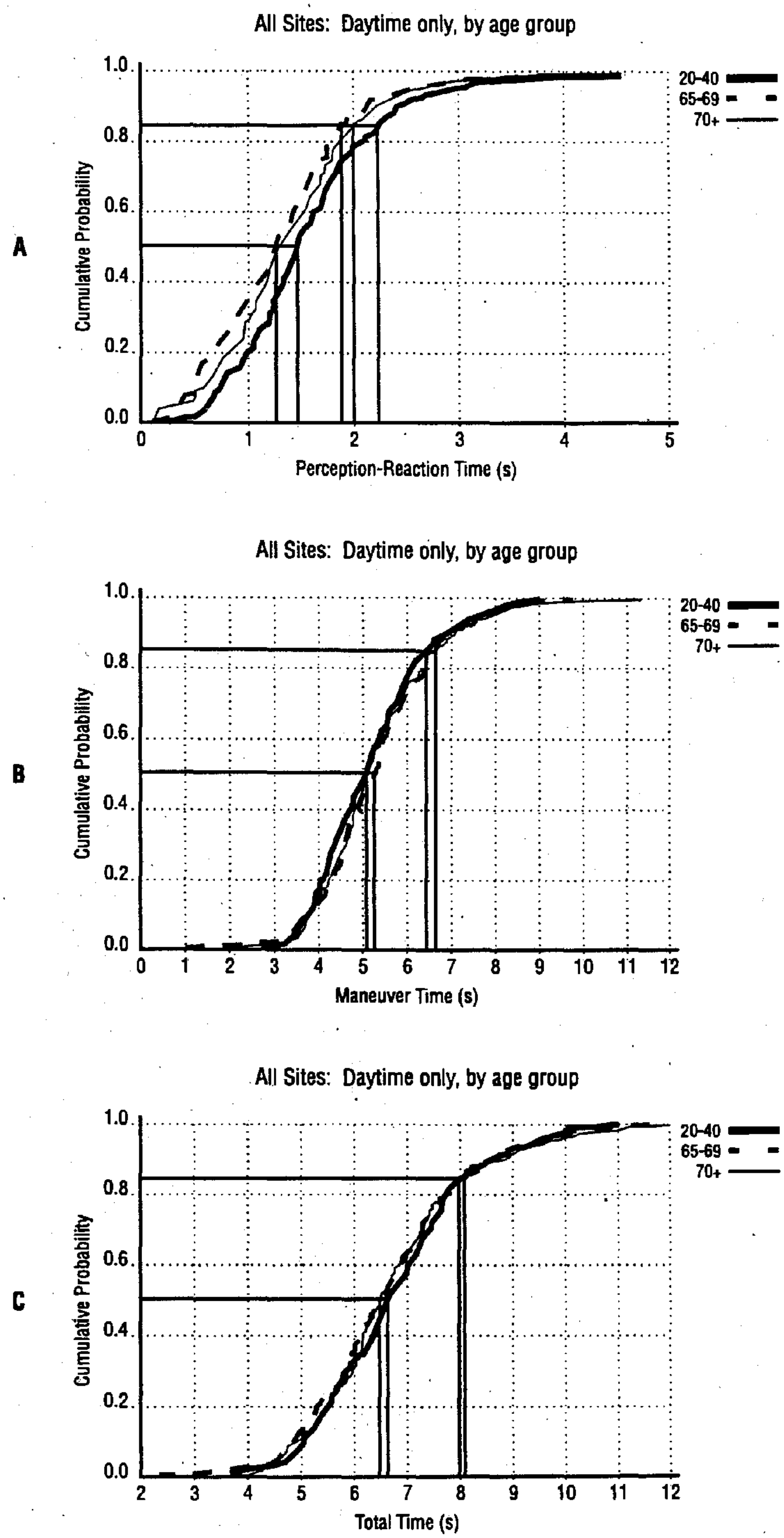
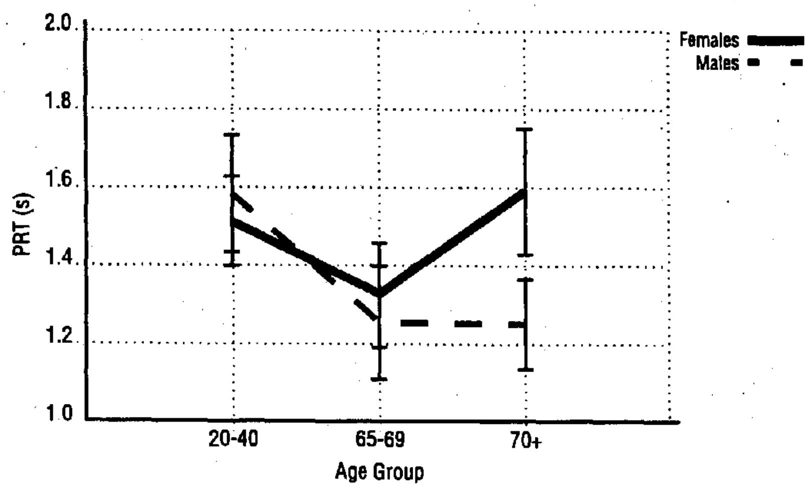


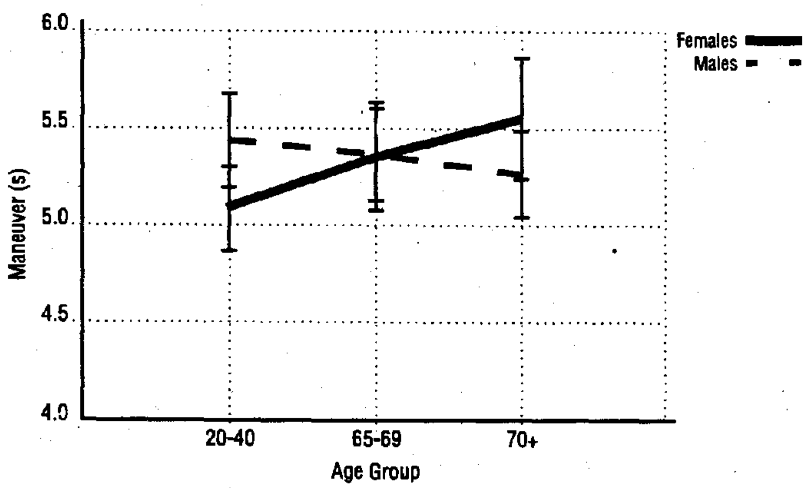
Figure 3. Cumulative probability for all sites: daytime only, by age group. (50th- and 85th-percentile points included in the figure.)

A



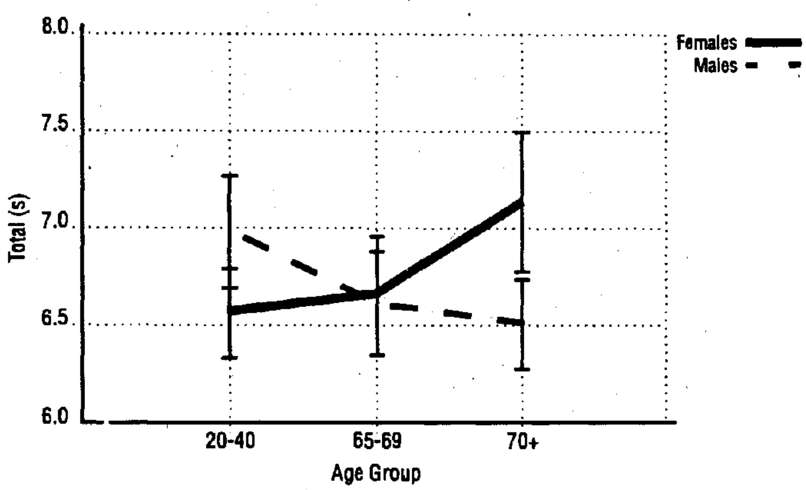
Note: Error bars are +/- 2 standard errors of the means.

B



Note: Error bars are +/- 2 standard errors of the means.

C



Note: Error bars are +/- 2 standard errors of the means.

Figure 4. Mean PRT, maneuver and total times by gender, age group.

Table 4. Analyses of variance of Case III intersection experiment.

Perception-Reaction Time					
Source	Sum-of-Squares	DF	Mean-Square	F-Ratio	P
Age	7.35	2	3.67	7.57	0.00
Gender	1.92	1	1.92	3.96	0.05
Age by Gender	4.53	2	2.26	4.66	0.01
Error	317.52	654	0.49		
Maneuver Time					
Source	Sum-of-Squares	DF	Mean-Square	F-Ratio	P
Age	2.65	2	1.33	0.79	0.45
Gender	0.09	1	0.09	0.06	0.81
Age by Gender	10.90	2	5.45	3.27	0.04
Error	1091.04	654	1.67		
Total Time					
Source	Sum-of-Squares	DF	Mean-Square	F-Ratio	P
Age	3.75	2	1.87	0.90	0.41
Gender	1.17	1	1.17	0.56	0.45
Age by Gender	29.11	2	14.56	6.99	0.00
Error	1361.85	654	2.08		

older and younger drivers use somewhat different strategies, with older drivers doing more of their search while they have already begun moving forward. To evaluate this, a detailed analysis of head turning was done for those sites that involved a right turn maneuver. For right turns, it is easy to tell when the driver is scanning for approaching traffic, since this involves looking to the left. Therefore, the video recordings were analyzed to determine the time of the last look to the left for each driver as he or she proceeded through the turn maneuver; this defined the point of termination of search for oncoming traffic. The data were analyzed both for the amount of time spent searching once forward movement had begun, and for the proximity of the last look to the completion of the turn maneuver. For neither measure was there any significant effect of age, gender, or their interaction.

The effect of vehicle transmission type (standard vs. automatic) was also examined. Only 8 percent of the subjects in the two older groups had standard transmissions in their vehicles. In contrast, slightly over half (52 percent) of the younger subjects had standard transmissions. It is conceivable that differences in PRT due to transmission type masked differences due to driver age. To examine this, t-tests were used to compare mean PRT for automatic and standard transmission vehicles. A mean PRT value was computed for each subject (averaged across all sites for which there was data for that subject). Separate t-tests were conducted for young subjects and for old subjects (two older groups combined). For the younger subjects, there was essentially no difference in the means (1.55 s with automatic, 1.49 s with standard). For the older subjects, those with automatic transmissions did have a faster group mean PRT (1.20 vs. 1.58 s). However, with PRT recorded for only five older subjects with standard transmissions, this difference is suspect and was not statistically significant. Furthermore, even the "slower" mean PRT for older drivers with standard transmissions was comparable to the times observed for younger drivers, with either type of transmission. Thus while it is conceivable that the predominant automatic transmissions might have resulted in shorter mean PRT for the older drivers, the evidence is against this. Furthermore, even if there were an effect of transmission type, there is no indication that older drivers would have longer PRT than younger drivers if researchers were to control for this.

Individual Sites. Summary data for individual sites are presented in table 5. When broken out by age groups, the relatively small number of observations results in more variability in the data. However, for most sites, the 85th-percentile PRT value is near or less than the 2.0 s design value. Also, consistent with the aggregate data, the group with the slowest PRT for most sites is the young group. Therefore, while the current design value corresponds to roughly the 85th-percentile PRT, this appears to encompass most older driver PRT. Table 5 shows group mean PRT for each site. Due to data loss, from numerous factors including traffic conditions, the number of observations on which each of the age group means is based varies considerably (from 7 to 23 observations). There does not seem to be any obvious systematic effect of site features, posted speed on the major roadway, or the subject's driving maneuver, on the magnitude differences between age groups. Due to the confounding of site features, the relatively few observations, and the possibility of sequence effects, there was no formal analysis of site characteristics as determinants of intersection PRT. No obvious effects of site features emerge from the pattern of findings, other than a possible tendency for low speed sites to have briefer PRT. However, while this experiment was intended to provide a range of representative geometric and operational features, it was not designed to formally evaluate them.

Discussion. The current design PRT value of 2.0 s approximates the overall 85th-percentile daytime PRT observed in this experiment; night PRT were slightly faster. Since the longest PRT were obtained for the younger group, the 2.0 s value appears to capture older driver PRT relatively well. To the extent that the driver model on which the current sight distance

Table 5. Site features and group mean PRT for each site.
(Number of observations shown in parentheses)

Site	Description	Speed mi/h (km/h)*	Maneuver	Mean PRT (20-40)	Mean PRT (65-69)	Mean PRT(70+)
1	4-lane, divided	55 (89)	Through	1.91 (16)	1.62 (16)	1.95 (9)
2	4-lane, divided	55 (89)	Left	1.72 (10)	1.26 (7)	1.46 (7)
3	2-lane, undivided, oblique	45 (72)	Left	1.74 (16)	1.67 (16)	1.50 (12)
4	2-lane, undivided, oblique	45 (72)	Right	1.71 (18)	1.34 (20)	1.39 (17)
5	4-lane, divided	55 (89)	Left	1.88 (13)	1.11 (16)	1.55 (18)
6	4-lane, divided	55 (89)	Right	1.74 (21)	1.29 (15)	1.36 (17)
7	2-lane, undivided	35 (56)	Right	1.37 (21)	0.91 (17)	1.28 (15)
8	2-lane, undivided	35 (56)	Left	1.09 (23)	1.07 (17)	1.25 (23)
9	2-lane, undivided, oblique	25 (40)	Left	1.38 (19)	1.37 (22)	1.37 (22)
10	2-lane, undivided	25 (40)	Through	1.38 (19)	1.10 (19)	0.99 (21)
11	2-lane, undivided, oblique	25 (40)	Right	1.57 (21)	1.22 (16)	1.34 (22)
12	2-lane, undivided, offset	40 (64)	Through	1.58 (11)	1.25 (10)	1.70 (7)
13	2-lane, undivided	35 (56)	Left	1.18 (14)	0.89 (11)	1.22 (14)
14	2-lane, undivided	40 (64)	Right	1.59 (10)	1.91 (12)	1.27 (10)

*mi = km x 0.621

equation is based is appropriate, the current value of the PRT parameter does not appear inappropriate for the older driver. However, for drivers of any age, the question of whether the 85th percentile is an acceptable design criterion remains an issue. As figure 3 indicates, the 90th percentile is approximately 2.3 s, and there were occasional extreme cases of 3 to 4 s. Nonetheless, for the older driver in particular, the current 2.0 s values incorporates the large majority of cases and does not differentially disadvantage the older driver. However, typical driver actions certainly do not follow the stop/search/decide maneuver sequence that is implied by the model. Experimental procedures were required to break visual search for conflicting vehicles on the approach to the intersections. Many drivers had a strong tendency to creep forward, search, creep forward further, search again, etc. Drivers continued to search, and appeared ready to terminate or modify their maneuver, even after they began moving into the intersection. Thus the AASHTO model may be best viewed as a particular case of driver behavior at intersections, rather than the most typical one. Other common actions afford drivers greater opportunity to search, terminate the maneuver, or reduce the maneuver to component actions. This suggests that the behavior model on which ISD is based is conservative, and the 2.0 s PRT value correspondingly ample.

Based on laboratory studies of reaction time and information processing, it might have been expected that older drivers would require longer PRT at stop-controlled intersections. The reasons why they do not are not known, although there are a variety of possibilities. For one thing, under the traffic situations studied, there was little urgency to the response of initiating forward movement. Since drivers were not operating near the limits of their capabilities, age differences in speeded reactions may not be expressed. Furthermore, because drivers act in a manner in which the maneuver can be terminated even once it has begun, decision criteria can be looser. Many older drivers may also have come to initiate movement more quickly as a compensatory mechanism for their slower maneuver times. It is also conceivable that the experimental procedures may have been more consistent with the normal behavior of older drivers, but more disruptive and unfamiliar to younger drivers. Forcing the driver to stop, search, and proceed may model a more typical response pattern of many older drivers, but less so for younger drivers. Although the specific factor of transmission type did not appear to be critical, other differences between the vehicles driven by older and younger people (e.g., acceleration capabilities, hood length, visibility from vehicle) conceivably could have an influence. These and other possible explanations may be speculated upon. However, the empirical fact remains that driving their own vehicles on actual roadways, older drivers did not require more time to initiate movement, or complete the maneuver, than did younger drivers.

Although older drivers did not appear to require more time at intersections, there was an age-by-gender interaction. Women in the oldest group were slower than men, for both PRT and maneuver times. This sort of interaction often has been reported in a variety of laboratory studies of reaction times or simulations related to driving.[17,26,47] It has also been our experience that women over age 70 are the most difficult subgroup to recruit for on-road driving studies, and thus the subgroup for whom there may be the greatest concern about sample bias. Therefore there should be some skepticism of the findings for this subgroup in particular for any on-road driving study. Nonetheless, nothing in the present experiment suggested that the current PRT value was inappropriate even for the oldest group of female subjects.

STOPPING SIGHT DISTANCE PRT

Method. SSD is one of the most important highway design concepts. It indicates the distance traveled before coming to a stop when a driver must brake in reaction to an unexpected event. SSD is determined by two components: the distance traveled during the time required to perceive and initiate action, and the braking distance required to bring the vehicle to a stop. SSD is therefore directly related to PRT. The current AASHTO equation uses a design value of 2.5 s for the term in the equation reflecting PRT.

The primary purpose of this experiment was to compare the PRT of older drivers with those of younger drivers and with the 2.5 s design value. In order to maximize ecological validity for the observed brake reaction times, the experimental procedure incorporated the following features: subjects drove their own vehicles; subjects traveled on actual roadways; the braking event was unanticipated; subjects were given sufficient time in the experiment, prior to the event, so that they were driving in a relatively relaxed, normal manner.

This experiment was run in two phases, having slightly different procedures. In both phases, subjects who had been driving a more extended route turned onto a four lane divided highway. This highway provides access to an Interstate highway, and then continues on for 0.7 mi (1.1 km) beyond the freeway entrances. This extended stub of the roadway beyond the freeway ramps is a fully designed and delineated roadway, but is closed to normal traffic by the use of barricades. Subjects were instructed that we had permission to continue on this road and drove around the barricades. The westbound portion of this divided roadway had no horizontal curves and only minor vertical curvature, with two 12-ft (4-m) lanes and 10-ft (3-m) shoulders on either side. Near the midpoint of this roadway section, there was some brush on a small berm in the median area. When the vehicle, traveling at approximately 40 mi/h (64 km/h), reached a criterion location, a large yellow highway crash barrel was remotely released. This barrel, hidden behind the brush, rolled down the berm and suddenly became visible emerging toward the roadway. Although it appeared to be rolling directly into the roadway, a set of chains held it to the shoulder area. The barrel emerged into view approximately 200 ft (61 m) in front of the vehicle; at 40 mi/h (64 km/h), this provided a time-to-collision of about 3.4 s.

Both phases of this experiment used subjects who thought the purpose of the study was to obtain their judgments of "road quality" while aspects of their driving were being recorded. The first phase of the brake reaction time experiment was simply a continuation of the Case III intersection PRT experiment; from the subjects' perspective, they were simply continuing the same procedure. The invehicle data collection system recorded the moment of emergence of the barrel from the video record of the roof-mounted camera, and the moment of the brake response was recorded via a force sensing resistor attached to the brake pedal. The second phase of the SSD study used a different group of subjects, who did not take part in the intersection study, but rather drove a different route, of about 3 mi (5 km), prior to encountering the barrel location. In the second phase, the subject's vehicle was not instrumented, although a complex-looking "dummy" device was attached to look like a sensor-based data collection system. A hidden roadside microcamera filmed the braking event from behind. The camera captured both the moment of emergence of the barrel and the moment of activation of the vehicle's brake lamps; this interval defined the PRT.

All sessions for the SSD PRT study were conducted in daytime; when weather was inclement or roads were wet, sessions were canceled. A total of 253 subjects were included in the testing. However, due to a high rate of data loss (discussed further below), valid data were obtained from a total of 116 subjects, the sample used in all the statistical analyses. The number of subjects, for this final sample, in each age group taking part in each phase of the study, are shown in table 6.

Table 6. Number of subjects: stopping sight distance experiment.

	20-40 Years Old		65-69 Years Old		70+ Years Old		TOTAL	
Phase 1	F	5	F	8	F	3	F	16
	M	5	M	7	M	12	M	24
Phase 2	F	10	F	14	F	12	F	36
	M	10	M	14	M	16	M	40
TOTAL		30		43		43		116

Results. Final Data Set. Valid test trials for the brake reaction situation were obtained from 116 of the 253 subjects initially participating. The high rate of data loss was due to a combination of various factors, including equipment failures, experimenter error, video problems, inappropriate subject behavior or failure to follow instructions, weather, unauthorized traffic at the site, and so forth. Subject loss was considerably higher for the first procedure, for a number of reasons: the much longer session resulted in more frequent weather changes and other problems; the invehicle data collection system was more sensitive and prone to problems than the onsite system; the triggering of barrel release from the vehicle was less reliable than the onsite sensors; "phantom" triggering of barrel release sometimes occurred (perhaps due to radio noise) and the barrel was already released when the test vehicle arrived; there was no onsite experimenter to continually monitor the barrel, the control equipment, and the site environment; problems were more difficult to detect and rapidly repair on-the-road. With all of these factors contributing, 36 percent of originally starting subjects in the first procedure yielded valid trials, while 55 percent yielded valid trials under the second procedure. Brake reaction times from the first and second sets of subjects were not significantly different ($t = -0.08$, 54 df), and the two data sets were combined for analysis of reaction times.

Driver Reactions. Two types of vehicle maneuvers were coded from the video records: brake responses and steering reactions. While discrete response times could be assigned to the brake responses, swerving was coded only for its occurrence and subjectively-judged severity. Of the 116 valid subjects, 101 (87 percent) made some overt vehicle maneuver in reaction to the emergence of the crash barrel. 36.2 percent swerved only, 7.8 percent braked only, and 43.1 percent both braked and swerved. Overall, then, 59 subjects (50.9 percent) braked in reaction to the barrel. Although most of the subjects (79.3 percent) showed some discernible steering response in reaction to the barrel, very few of these were severe. Most "swerves" were moderate but clearly detectable changes of heading away from the barrel.

Although brake reaction times did not differ between the first and second sets of subjects, the proportion of subjects who did brake was significantly higher in the first procedure (75 percent versus 38 percent; Chi square = 14.15, 1 df; $p<0.001$). This resulted in a smaller brake reaction time data set than anticipated. The reasons for the substantially lower rate of braking in the second procedure are not clear. The situation was designed to appear similar from the subject's perspective. Among the general procedural differences were: the amount of driving done prior to the incident (more than 1 hour vs. about 10 minutes); the method for activating the barrel (experimenter-triggered vs. sensor-triggered); the method of detecting the brake response (pressure on brake pedal vs. activation of brake lamps); the judgments of road quality made by subjects in the first procedure; the particular experimenters in the car with the subject; time of year. While any of these might have had some effect, care was taken to keep the situations very similar from one procedure to the other. Whichever are the key factors, the differences do suggest that the probability of braking can be influenced by relatively subtle procedural factors.

Brake PRT. Although braking was detected for 59 subjects, an actual measure of PRT was derivable from the data records for only 56 of these. Analyses of PRT are therefore based on 56 subjects. Brake reaction times were subjected to a two-factor (age group and gender) analysis of variance. Neither main effect of age nor gender was statistically significant. The interaction of age and gender was short of conventional significance levels ($F=3.08$, $p=0.055$). The interaction reflects the particularly short mean reaction time observed for the young female group (1.22 s), while the other age-by-gender group means ranged from 1.40 to 1.65 s.

Table 7 presents the mean (and standard deviation), median, and 85th percentile brake reaction times for the entire group of subjects, and for subgroups based on age and gender. Figures 5 through 7 present these data in the form of cumulative percentage plots. Some of the key points to notice are:

1. The mean brake reaction time, overall and for various subgroups, is about 1.5 s, with a standard deviation of about 0.4 s.

2. The median brake reaction time is approximately 1.4 to 1.5 s.

3. The 85th percentile brake reaction time is approximately 1.9 s.

4. Virtually all response times are captured by the current 2.5 s design parameter for brake perception-reaction time. The slowest response time was 2.54 s; the next slowest was 2.39 s.

5. The distribution of brake reaction times for the young group was bi-modal.

The majority of response times for the younger group (10 of 14) were 1.43 s or faster; the four remaining times were 1.93 s or slower. In contrast, for the two older groups, roughly half of the reaction times (20 of 42) fell in the half-second interval between these values. Given the relatively small number of observations in the young age group, differences in the distributions must be viewed skeptically. Nonetheless, more than 70 percent of the younger subjects had reaction times of 1.43 s or less, while only 40 percent of the older subjects reacted this rapidly. Table 8 summarizes these distributions in tabular form, showing the frequency and percentage of cases falling in various categories of response speed. As reference to the table shows, younger subjects showed no response times between 1.50 and 1.75 s, the most frequent category for the oldest group. Due to the small cell frequencies (particularly for the younger group which had fewer subjects), statistical comparisons of the age distributions shown in table 8 were precluded.

Table 7. Mean (standard deviation), median, and 85th-percentile brake reaction times.

	$\bar{x}$ (s.d.)	50%	85%
All (n=56)	1.51 (.39)	1.44	1.91
Male (26)	1.49 (.34)	1.42	1.88
Female (30)	1.52 (.44)	1.47	1.93
20-40 Years (14)	1.44 (.48)	1.35	1.97
65-69 Years (18)	1.59 (.38)	1.47	1.92
70+ Years (24)	1.49 (.34)	1.52	1.72

Table 8. Distribution of brake reaction times for age groups.

	20-40 Years	65-69 Years	70+ Years	All Subjects
Brake Reaction Time				
<1.25 s	5 (36%)	1 (6%)	5 (21%)	11 (20%)
1.25 - 1.49 s	5 (36%)	8 (44%)	6 (25%)	19 (34%)
1.50 - 1.74 s	0 (0%)	4 (22%)	9 (38%)	13 (23%)
≥1.75 s	4 (29%)	5 (28%)	4 (17%)	13 (23%)

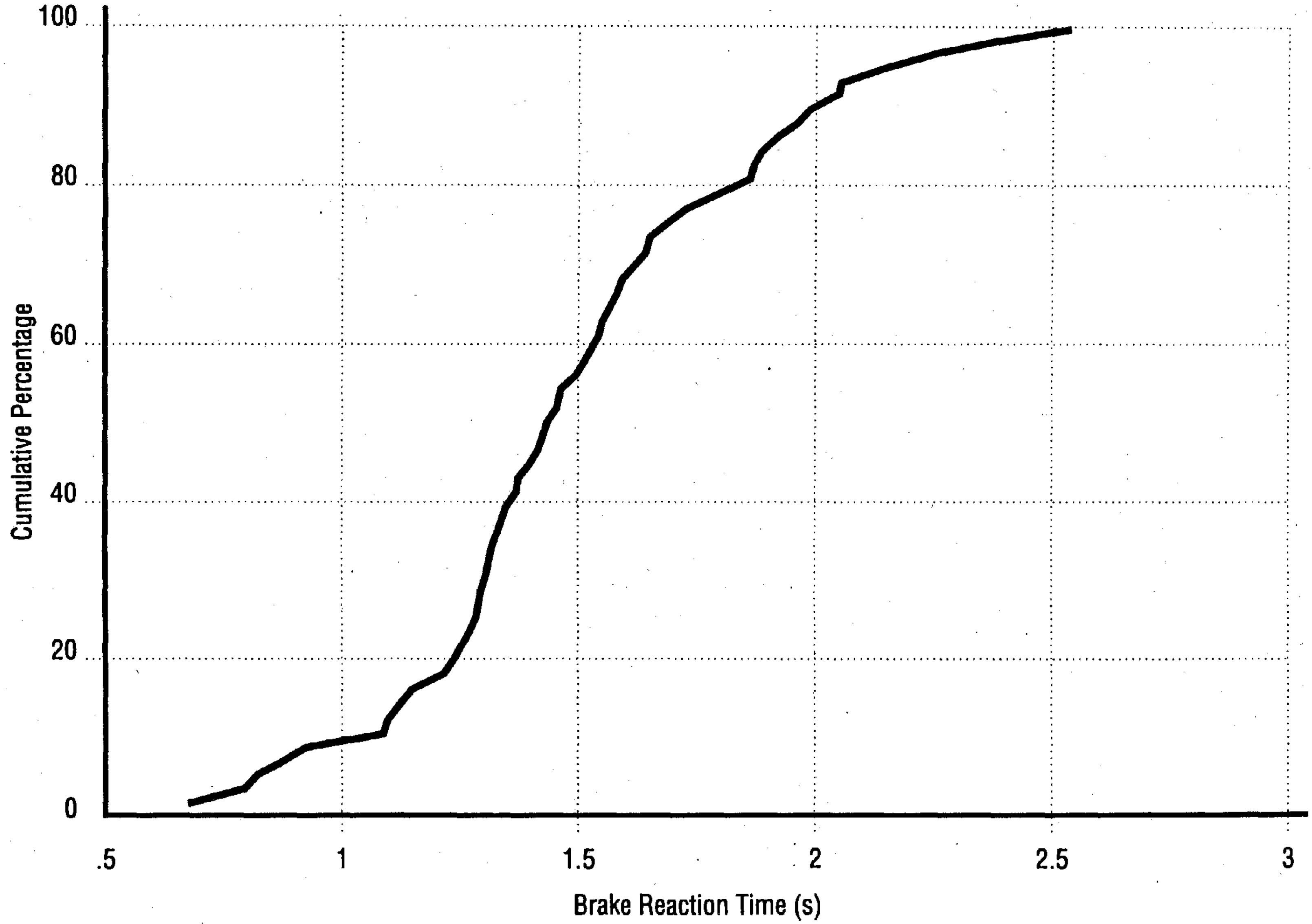


Figure 5. Brake reaction time for all subjects (n=56).

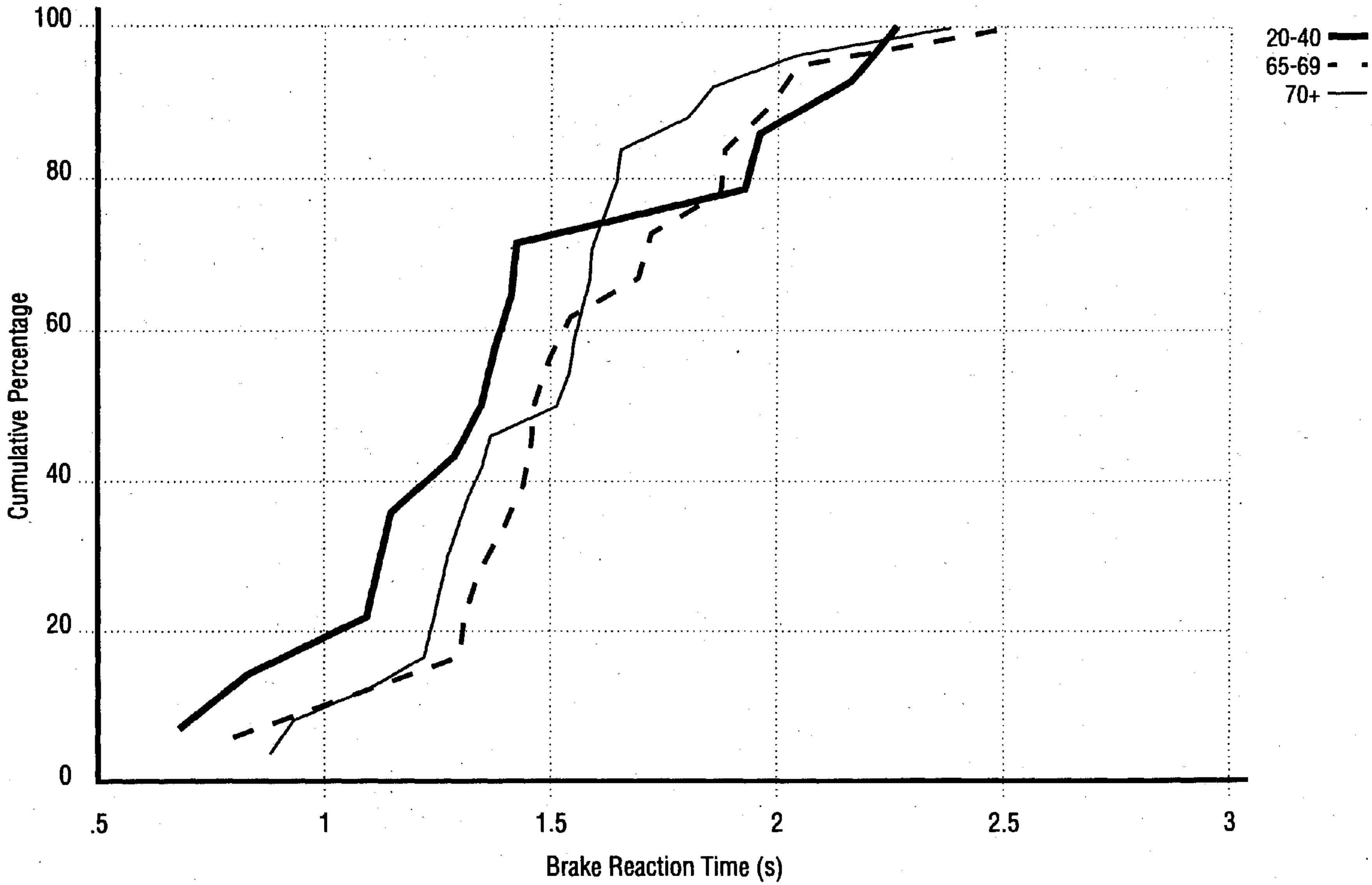


Figure 6. Brake reaction time by age group.

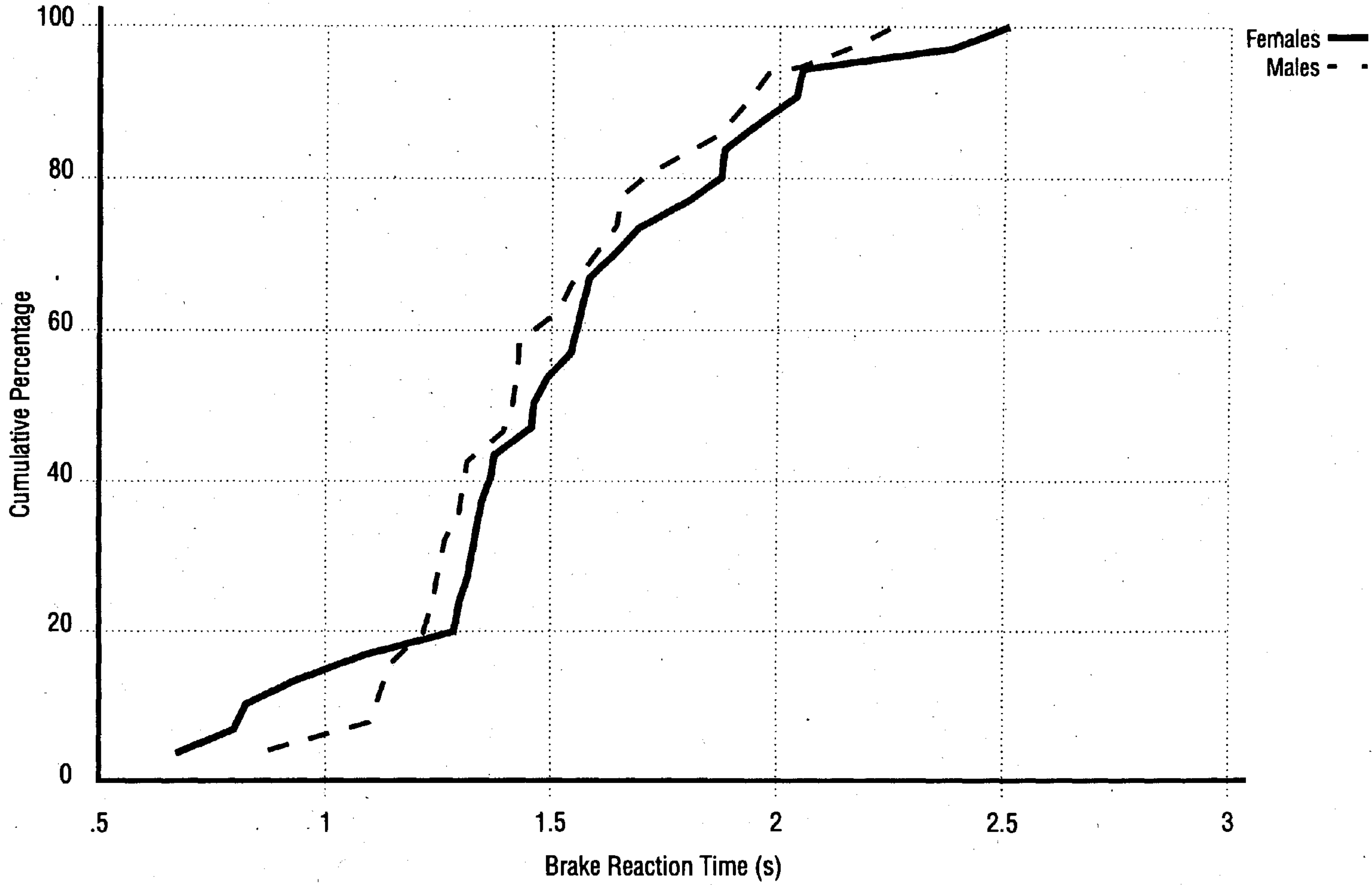


Figure 7. Brake reaction time by gender.

__Steering Actions__. Steering reactions were subjectively coded for the degree of swerve, based on the video records. These were classified into four categories:

	n	%
No discernible swerve	22	19.3
Slight swerve	55	48.2
Distinct swerve	35	30.7
Severe swerve	2	1.8
TOTAL	114	100%

(2=missing)

The data were examined to see whether the brake reaction was related to the steering reaction. No clear pattern was seen with respect to the proportion of drivers that braked. However, more substantial steering actions were associated with somewhat longer brake reaction times. Those drivers showing slight or no swerve, and also braking (n=35), had a mean brake reaction time of 1.44 s. Those showing more distinct or severe swerves, and also braking (n=20), had a mean brake reaction time of 1.70 s. Thus those who reacted to the emergence of the barrel with a more pronounced steering action also took about a quarter-second longer to activate the brake. This difference was statistically significant ($t = 2.51$, 52 df; $p<0.02$).

Since subjects drove their own vehicles, the type of transmission (automatic vs. standard) was a possible confounding factor in interpreting the findings. Nearly all the drivers in the two older groups (94 percent) drove with automatic transmission, but only about two-thirds of the drivers in the young (20 to 40 year old) group did. Therefore, the influence of transmission type was analyzed for the young driver group (since only a few older drivers had standard transmissions, it was not possible to evaluate this factor within the older groups). Transmission type had no discernible effect on the type of driver reaction (brake, swerve) or the speed of braking. Thus this factor does not appear to be a critical consideration in determining brake PRT values and apparently does not account for the absence of observed differences between age groups.

__Discussion__. The sudden emergence of a rolling barrel from the side of the roadway was effective in simulating a real unexpected roadway event, and about 9 out of every 10 subjects showed some overt driving response (brake activation or discernable steering) to that event. However, braking in reaction to the barrel occurred for only about half the subjects. Debriefing of the subjects following the experiment indicated that the barrel release was convincing as a real occurrence rather than a contrived experimental event. There was a great deal of variability in the verbally expressed sense of danger or urgency provoked by the barrel release. Based on the initial procedure used, it appeared that about three-fourths of all drivers would respond to the barrel by braking. However, the second procedure obtained only slightly more than half of this rate. The method did not result in any skidding, loss of control, or other potentially dangerous situations. The procedure therefore appears useful for studying driver brake reaction time, assuming the factors leading to the lower braking rate in the second procedure can be identified and corrected. It should be noted that the proportion of vehicles braking in reaction to some contrived event has been highly variable, and usually only moderate, across a variety of previous on-road studies. Summala has observed that it is difficult to induce reliable braking except under the most dangerous situations, and has argued that steering latencies may be more easily and appropriately studied.[34] Among the on-road studies of braking, Triggs and Harris found that for drivers encountering a "protruding vehicle with tyre change" when going over a hill crest, 44 percent of drivers braked in daytime and (with the vehicle lit) 64 percent braked at night.[31] These authors also found that the proportion of cars that braked in response to a lead vehicle's brake lamps was highly dependent on following headway. Various other studies of reaction to a lead vehicle's brake lamps have reported percentages of responding drivers ranging from about 30 percent to about 80 percent. Thus the approximately 50 percent braking rate of the current experiment is well within the typical range of other studies. The variability between studies, and between the two procedures of this experiment, suggests this percentage is sensitive to procedural factors.

The current design value of a 2.5 s brake reaction time appears adequate to incorporate the full range of drivers, including older drivers. For the group of subjects as a whole, and for each age group independently, the findings can be characterized as showing a mean brake reaction time of about 1.5 s, a 50th percentile time of about 1.4 to 1.5 s, and an 85th percentile time of under 2.0 s. Virtually all observed reaction times were within the 2.5 s criterion, despite the fact that the brake reaction times recorded here were somewhat longer than those observed in other on-road studies (generally by about 0.15 to 0.35 s). (See references 33,31,32,29,30.) While the reason for these longer times is speculative, it is quite likely that it is due to the emergence of the "hazard" from the side of the road. Other studies have used events more central to the field of view, thus presumably requiring less search and detection time. In this regard, the present study provides a possibly more conservative scenario for estimating driver reaction times. Drivers in this study also had latitude to steer around the emerging barrel, rather than simply braking; as noted, those who made more substantial steering maneuvers also showed somewhat longer brake reaction times. This might also account for some differences with other experiments, such as car following in traffic. Despite the slower observed reaction times, and reasons to believe this was a conservative method for obtaining brake reaction times, the 2.5 s PRT stopping sight distance design criterion appears to encompass the findings adequately.

As in a number of previous studies that have measured on-the-road brake and/or steering reaction times, this experiment did not use a "hazard" event that corresponds to the 6-in (152 mm) high object used to define sight distance by AASHTO. AASHTO indicates that this is an arbitrary value that might be representative of the lowest debris object that might create a hazardous condition.[10] This criterion has been severely criticized, and is highly unrepresentative of the types of objects actually involved in collisions.[38,44,2] For comparison of PRT for older and younger drivers, such a small target object also presents interpretive difficulties, because the situation essentially results in a study of the effects of visual acuity, rather than more representative differences in the time required to recognize and react to hazardous events. The AASHTO definition of SSD also refers to the object as being in the vehicle's path. The present experiment quite intentionally chose to use a target object that emerged from a more peripheral location, for the following reasons:

- It represents a more conservative test, because as the literature search on reaction time indicated, responses to objects in the central visual field are faster than those to more peripheral events. The search time component of PRT is minimized if the object is already centered in the line of sight.

- The use of an object emerging from the side is more appropriate for determining whether older drivers are substantially slower in reacting. The reaction time literature clearly shows that older people have greater deficits in detecting or attending to objects as the become more peripheral. The concept of "useful field of view" has been related to older driver problems and accident involvement.[19] Thus if we wish to know whether older drivers require more PRT, we should use those situations in which this deficit is likely to be expressed.

- Experiments that have used an object placed in the lane have of necessity required locating the object at a site with limited sight distance; if sight distance was long, there would be no "urgency" to respond when the object was initially seen, so that response times would not be meaningful.[33] However, there is a concern that older and younger drivers might differ in the caution they show in approaching a limited sight distance condition, such as a sharp vertical or horizontal curve. Because of the visual uncertainty of what lies ahead, there may be an expectancy of the need to respond. In particular, older drivers may be more cautious and ready to react. For this reason, a more appropriate test of whether older drivers required more PRT would be a situation in which they could not compensate by anticipating a possible need to react. Therefore, a clear tangent section was chosen, with the hazard emerging under conditions for which the driver could have no expectancy.

Thus for all these reasons, it was deemed more appropriate to conduct the SSD PRT experiment using a hazardous object emerging from the side of a tangent roadway section, rather than using a small target placed in the vehicle lane. It provides a more conservative test of the adequacy of the 2.5 s design value, and of the potential disadvantage of older drivers, but without reducing the situation to an improbable one that is primarily influenced by visual acuity limits.

Older drivers did not show significantly longer brake reaction times than younger drivers. While this is not consistent with the laboratory findings regarding age and reaction time, it is consistent with the previous major on-road study of age and brake reaction time.[33] A variety of possible explanations exist.[9] However, two points bear particular comment here. First, although the mean brake reaction times did not differ between age groups, the distributions of reaction times appeared quite different. Younger subjects showed a higher proportion of short reaction times; however, the occurrence of long reaction times in this group precluded mean differences from being statistically meaningful. It may be noteworthy that the oldest group of subjects showed the fewest long (>1.75 s) reaction times. Thus while there is little difference in the mean reaction times, or even in the 85th percentile times, this does not necessarily imply that the older and younger groups respond in the same manner. The relatively small samples preclude taking the precise form of these age-group distributions too literally, but the general point that they may well differ is important.

A second point is that the test situation, as well as most real life braking situations, does not require the subject to respond in an all-or-none manner as rapidly as possible (as do laboratory reaction time studies). In fact, except for the very most extreme emergencies, it may be an unwarrantedly dangerous maneuver for a driver to go into immediate full braking. Normally some evaluation is done prior to and/or in parallel with the initiation of responding, options (including steering) are evaluated, and braking is conducted in a controlled manner. Thus there is no reason to presume that subject drivers were reacting at the absolute limit of their capabilities. This might obscure age effects that may be more evident at the limits of performance.

In summary, this experiment obtained typical (mean and median) brake reaction times of about 1.5 s, and this did not differ among age groups. The current 2.5 s PRT value used for stopping sight distance equations captured virtually all responses, and the 85th percentile times, even for older subjects, were about a half-second below this value. Consistent with other literature, actual braking was observed for about half the subjects, although some combination of braking and/or steering was observed for most drivers.

The absence of substantially slower brake PRT among older groups provides an illustration of how the factors of expertise and compensation in complex skills can maintain performance even in the face of reduced capabilities. Virtually all of the component psychomotor processes that underlie PRT -- information processing rate, visual search time, response initiation, movement time, etc. -- have been shown to slow with age, in laboratory studies. Age-related compensation is poorly understood for driving, as it is for various other skilled tasks.[16] Furthermore, the mechanisms involved in compensation for one aspect of performance might be related to degradation in other aspects of performance (e.g., braking may be more "all-or-none," providing a greater risk of rear end collisions or loss of vehicle control). One possible explanation for the absence of a difference between age groups is that older drivers might be responding in a more reflexive, stereotyped manner. Younger drivers may be prone to do more evaluation before responding, or respond in a more gradual or controlled manner, using their faster information processing capabilities to refine the response, rather than quicken it. It was the subjective opinion of the primary research assistant who accompanied the drivers that the older drivers tended to make more evident and dramatic foot movements while braking, although he did not notice a subjective sense of more severe deceleration. This observation is also consistent with the data of Olson et al., whose instrumentation allowed the total PRT to be segmented into a "perception time" (from first target visibility to release of the accelerator) and a "response time" (from release of the accelerator to stepping on the brake pedal).[33] Although there was little difference between age groups in the total PRT, the older group actually had <u>faster</u> "response times" (estimating from figures, about 0.1 s faster at the 50th percentile and about 0.2 s faster at the 90th percentile). Thus based on our observations and the Olson et al. findings, it may be that in a situation where there is a surprise need for possible braking, older drivers are more consistent in making a rapid move to the brake pedal, once the hazard has been recognized.[33] The response may be more stereotyped, and subject to less evaluation and modulation. Whatever the reason for the absence of observed differences in overall brake PRT between age groups for SSD situations, it is none the less clear that most older drivers can continue to react with appropriate swiftness, even to an unanticipated braking event. It should be noted, however, that where the stimulus events and required driving maneuvers are more complex and ambiguous than emergency braking, there might be more deleterious effects of age.

DECISION SIGHT DISTANCE PRT

Method. As a geometric design element, Decision Sight Distance (DSD) is intended to provide the driver with sufficient sight distance to detect an unexpected or difficult-to-perceive information source or hazard, recognize the situation and its threat potential, and complete an appropriate maneuver safely and efficiently. These sight distance criteria were established for complex highway situations such as interchanges, lane drops, high-speed merges, toll booths, and intersections where unusual or unexpected maneuvers are required. Because decision sight distance is defined for a less restrictive maneuver than the sudden braking assumed for stopping sight distance (SSD), DSD values are substantially longer and provide an additional margin for error. Although the current 1990 edition of AASHTO's *A Policy on Geometric Design of Highways and Streets* does not specify the PRT assumed in the prescribed DSD values, they can be derived using the DSD equations and the previous 1984 edition.[10,12] These PRT values range from 1.5 to 3.0 s for the detection and recognition component plus an additional 4.2 to 7.0 s for the decision and response initiation component. The total PRT ranges from 5.7 to 10 s depending on the design speed.

The field studies upon which the PRT calculations were based were very limited and gave no specific consideration to the older driver. However, it is in precisely the types of highway situations for which the DSD criteria were developed that older drivers may tend to have more difficulties related to information processing and decision making. Therefore, it is appropriate that the PRT for decision sight distance be re-evaluated with specific consideration given to the older driver. The objective of this experiment, then, was to determine the distribution of PRT for drivers of different age groups in response to complex geometric or operational conditions where DSD criteria would apply.

As an overview, the experiment had subject drivers from three age groups (20 to 40, 65 to 69, and 70+) drive their own vehicles along a 35-mi (56-km) route designated by the experimenter. A video camera was mounted on the roof of the vehicle to record the entire trip. During the course of their driving, subjects encountered 13 situations (sites) where decision sight distance criteria were applicable. The sites were chosen to provide a mix of complex freeway and arterial situations and included five freeway lane drops, one freeway left exit, five arterial turn-only lanes, one arterial lane drop, and one complex intersection.

Each situation/site required the subjects to make a lane change in order to avoid a lane drop or a turn-only lane. In their pretest instructions, subjects were told that they were to always continue *straight* through any intersection or interchange encountered along the route and were responsible for making any maneuvers necessary to do so. When they found themselves in one of these decision sight situations, subjects had to recognize that they were in a lane that would force them to make an undesired turn, decide on an appropriate lane change that would allow them to continue straight through the site, and execute that lane change. Subjects were instructed to give an immediate verbal response whenever they recognized that a maneuver was necessary. Since in every situation the required maneuver was a lane change, subjects were told to give a simple "I need to move left" or "I need to move right" the moment they recognized the need for a lane change. The response was recorded by the video camera via a wireless microphone. After giving a verbal response, the subject was free to perform the lane change. The subject also briefly described whatever cue first conveyed the need to make the maneuver.

Getting subjects to verbalize their intended actions as soon as they had decided on a lane change was a critical part of training, since making lane changes is almost reflexive for experienced drivers. Each subject was taken through two practice sites before the data collection began. Subjects were given additional practice runs if the experimenter felt that they were not grasping the procedure or verbalizing their actions quickly enough. Two practice sites were found to be sufficient for most subjects.

Each test site had "cue points" such as traffic signs, pavement markings, signal heads, and site geometry which could alert drivers to the need to make a lane change. The PRT measured in this experiment was the time interval from the point when a cue first became visible to the point at which a subject had detected the cue, recognized the situation, decided on an appropriate lane change, and verbalized their intended action. The "point of first visibility" for a cue was the point at which a sign became legible or a pavement marking became clearly discernable to the driver. The general location of these points were determined beforehand by the research team, but since the visibility and legibility of cues was often dependent on lighting, weather conditions, and the presence of other vehicles, the experimenter frequently determined the points of first visibility for cues as the drive progressed. As each cue became visible/legible, the experimenter silently activated a signal lamp that was recorded by the video camera. The time interval from the activation of the lamp to the subject's verbal response was later measured from the videotape to obtain the PRT. There is a drawback to this method in that the points of first visibility were based on the experimenter's vision and not that of the subjects. Unfortunately, there was no satisfactory way to avoid this problem (subjects could not determine these points for themselves since this would have required them to be alerted to the presence of the cues beforehand).

After each site, the experimenter recorded the cue to which the subject responded and asked whether the subject had been familiar with the site beforehand. If a subject was familiar with a site beforehand, these data were not included in the subsequent analysis. In general, it was found that while some subjects were familiar with portions of the course, the majority of the subjects were familiar with at most one or two sites, and many were not familiar with any of the sites.

The following is an example of the procedure at a typical site. When approaching a freeway right-lane drop, the experimenter would direct the subject to drive in the right lane. Subjects were not made aware that they were approaching one of the sites and the experimenter did not provide any prompts or guidance in making lane changes. When the cue for that site (sign or pavement marking) became visible, the experimenter would silently activate a signal lamp in the video camera. The subject would continue driving until he/she recognized the cue that indicated the right lane was ending. After recognizing the situation, the subject would announce, "I have to move left", and proceed to make the lane change. Upon completion of the lane change, the experimenter activated a second signal lamp in the video camera to record the end of the maneuver. The end of the maneuver was taken to be the point at which the subject had completed an appropriate lane change. In general, a lane change was judged complete when the subject had moved the entire vehicle into the adjacent lane. Occasionally, however, we found that a few drivers would not make clearly defined lane changes but would instead "drift" between lanes (i.e., straddle two lanes for long distances). In these cases, the experimenter would judge a maneuver complete when it was felt that the subject had moved the vehicle enough to adequately respond to the situation. These cases were not common and were reviewed on the video tapes to confirm acceptable completion times. Afterwards, two values were measured from the video record: (1) the time interval from when the cue first became visible (as defined above; indicated by the first signal lamp) to the point at which a subject had detected the cue and given a verbal indication of intended action (this was the PRT), and (2) the time interval from the subject's initial verbal response to the actual completion of maneuver (this was the maneuver time).

Tests were conducted both during the day and at night. The numbers of participating subjects for each age group are shown in table 9. The original plan called for an equal number of males and females for both day and night conditions; however, this was not achieved because of difficulty in finding older women who were willing to drive at night. There were a total of 98 subjects with no carry over between the daytime and nighttime runs.

Table 9. Number of subjects: decision sight distance PRT experiment.

Age Group	Gender	Day	Night	Total
20-40	F	7	7	14
	M	7	7	14
65-69	F	10	7	17
	M	8	10	18
70+	F	10	3	13
	M	12	10	22
Total		54	44	98

After each experimental run, the subjects were asked to fill out a questionnaire which detailed their driving habits, driving preferences, and any medical conditions that might have affected their driving.

Results. Old vs. Young PRT. Table 10 presents mean PRT for each DSD situation by age group for both day and night conditions. Sites 10 (freeway left exit) and 13 (arterial turn-only lane) have not been included in the analysis because they yielded inconsistent data. When comparing the mean PRT values for daytime runs, it appears that older drivers displayed longer PRT than the younger group. For all sites, except site number two (a freeway lane drop), either one or both of the older age groups had longer mean PRT than the young group. T-tests were performed on the data to determine whether differences in PRT between older and younger drivers were statistically significant. A shaded cell in table 10 indicates that there is a statistically significant difference between the value in that cell and the corresponding value for the 20 to 40 age group at a 95-percent confidence level. There were statistically significant differences between one or more of the older groups and the younger group at five of the sites.

Table 10. Mean PRT by site, age, and day/night condition.

Site	DAY PRT (s) Age Group			NIGHT PRT (s) Age Group		
	20-40	65-69	70+	20-40	65-69	70+
1. Freeway Lane Drop	4.05	4.27	5.72	3.73	4.21	5.97
2. Freeway Lane Drop	6.56	4.35	5.41	4.44	5.02	4.26
3. Arterial Turn Lane	2.76	2.46	3.57	3.28	3.74	3.79
4. Arterial Turn Lane	2.68	6.01	4.42	4.29	3.57	3.90
5. Arterial Turn Lane	1.60	2.53	2.88	2.41	2.39	2.98
6. Complex Intersection	2.83	2.51	3.71	2.56	3.10	4.83
7. Freeway Lane Drop	2.16	3.12	3.02	3.07	2.80	2.49
8. Freeway Lane Drop	2.88	6.64	4.51	5.63	4.90	5.35
9. Freeway Lane Drop	4.30	6.28	6.31	3.80	4.85	4.39
11. Arterial Turn Lane	2.05	3.38	4.78	3.63	3.54	2.84
12. Arterial Turn Lane	2.52	6.27	6.99	2.75	2.20	2.59

For the nighttime conditions, one or both older age groups displayed higher PRT than the young group at six of the sites; however, at only two sites were the differences between one or both of the older groups and the young group statistically significant at a 95-percent confidence level.

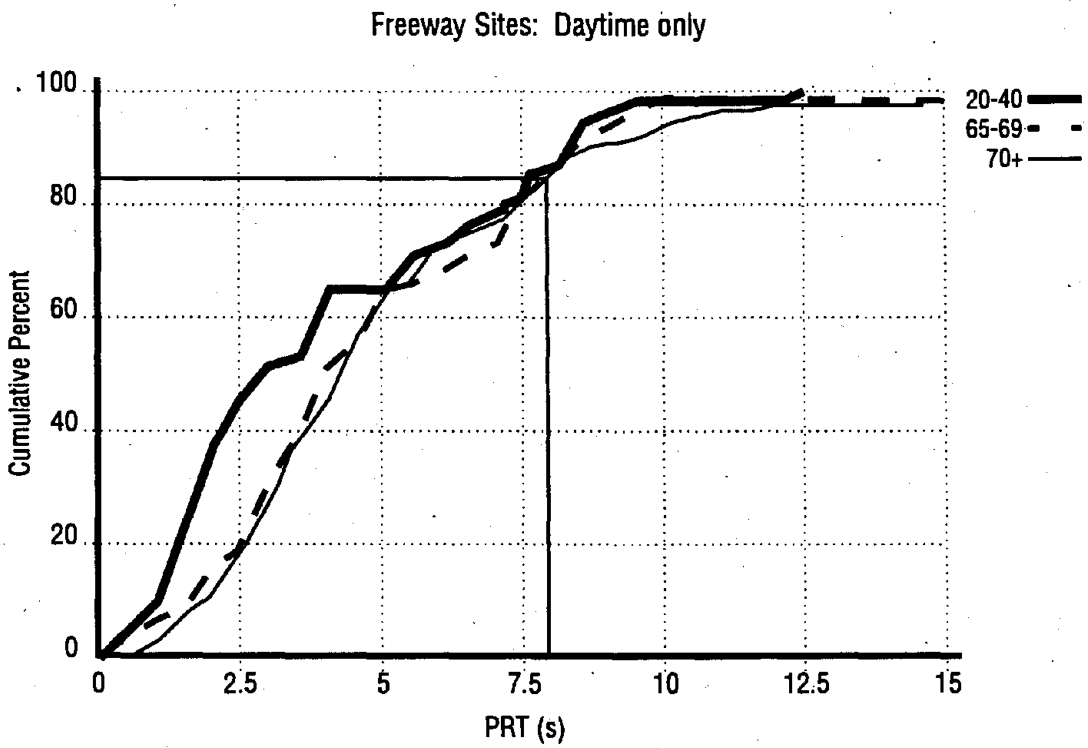
Experimental PRT Values vs. AASHTO Values. As a way to summarize all of the PRT data, 11 of the 13 sites were grouped into two common types: freeway lane drops and arterial turn lanes. Again, sites 10 (freeway left-exit) and 13 (arterial turn lane) were dropped from the analysis because of inconsistent data. The PRT values for sites within these groups were pooled to form separate frequency distributions. These are shown by age group in figures 8 and 9.

The 50th and 85th percentile PRT values are summarized for the two groups in table 11. Looking first at the freeway sites, it can be seen that the 85th percentile daytime PRT values were fairly consistent for all three age groups (7.6 - 7.8 s). The differences between the age groups are more pronounced at the 50th percentile level, but seem to disappear at the 85th percentile level. While many younger drivers appear to have had quicker PRT than the older drivers (in freeway situations), there does not appear to much difference between the 85th percentile drivers in each group.

At the arterial sites, however, the 85th percentile daytime PRT were considerably shorter for the younger group than for the older groups. The 85th percentile values were again fairly consistent for the older groups (7.6 and 7.1 s) but were substantially longer than the 4.2 s found for the younger group.

The DSD values provided in the 1990 AASHTO Green Book assume PRT values of 10.0 s for urban freeways and 9.5 s for urban arterials. In freeway situations the 85th percentile PRT values for all age groups fell within the 10.0 s recommended by AASHTO. Likewise for the arterial sites, the 85th percentile PRT values for all age groups fell well within the 9.5 s AASHTO standard. Even though the PRT values measured in this experiment did not necessarily include the "response initiation" component of the premaneuver time considered in the original DSD equations, the response initiation time is typically very small and the results obtained here appear to be in agreement with the values for the current AASHTO standard.[10]

__Day vs. Night__. It can be seen from table 11 that the 85th percentile nighttime PRT were shorter than the corresponding daytime PRT for both the freeway and arterial situations, with the exception of the 20 to 40 age group at the arterial sites. This parallels the shorter night PRT also observed in the Case III intersection PRT experiment, although the causal basis is not necessarily the same. Although the reasons for the shorter night PRT in the DSD experiment are not known, there may have been two factors which came into play. First, visibility at night was often restricted to the range of the vehicle headlights, thus reducing the range at which cues became visible. Nighttime driving therefore had the effect of narrowing the range in which cues could be detected and thus may have also shortened the times for cue detection and recognition. This would seem to be supported by the fact that the variances in PRT were smaller during the nighttime for 2/3 of the age group/site data sets. It can also be seen from figures 8 and 9 that differences in PRT between age groups were less pronounced at night, indicating that nighttime may have an equalizing influence on the age groups. A second possibility is that the difference in traffic volumes between the day and night time runs may have influenced the PRT. Most of the course was over major freeways and arterials that were heavily used during the day time. Traffic levels were generally lighter at night and may have allowed drivers to devote more of their attention to observing traffic signs and the roadway. The extent to which these were factors is not certain, however. In the end, the highest 85th-percentile PRT values were found in the daytime and these are the values that will be used to assess the adequacy of current AASHTO standards.



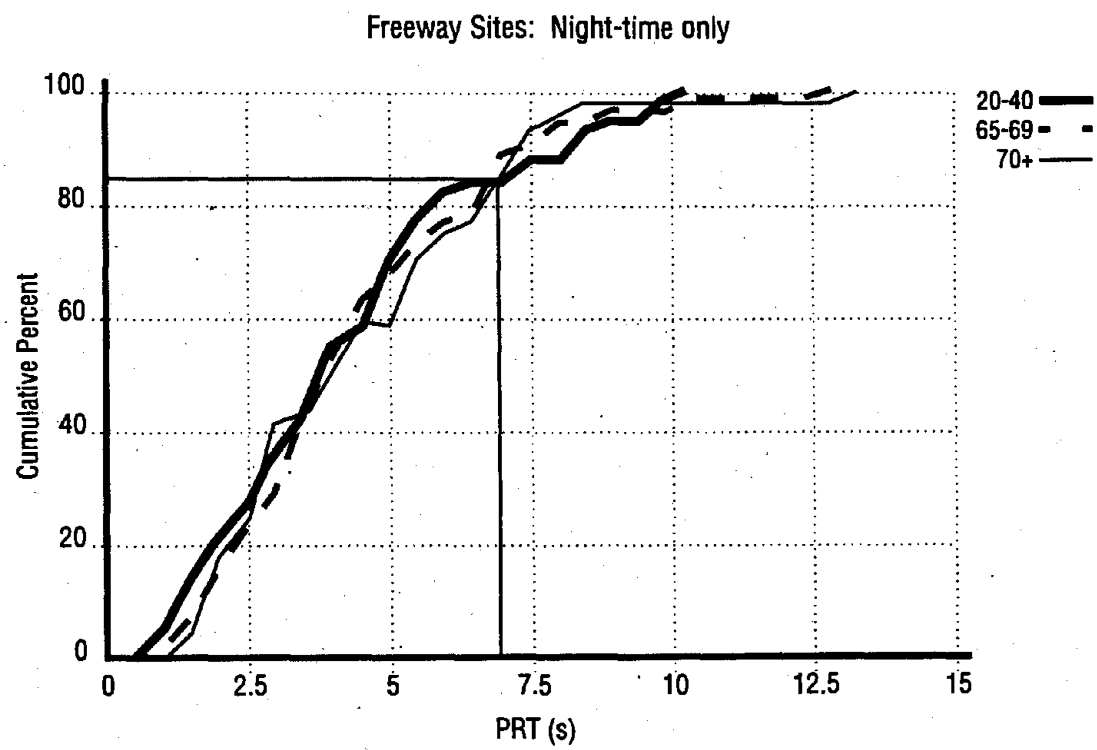
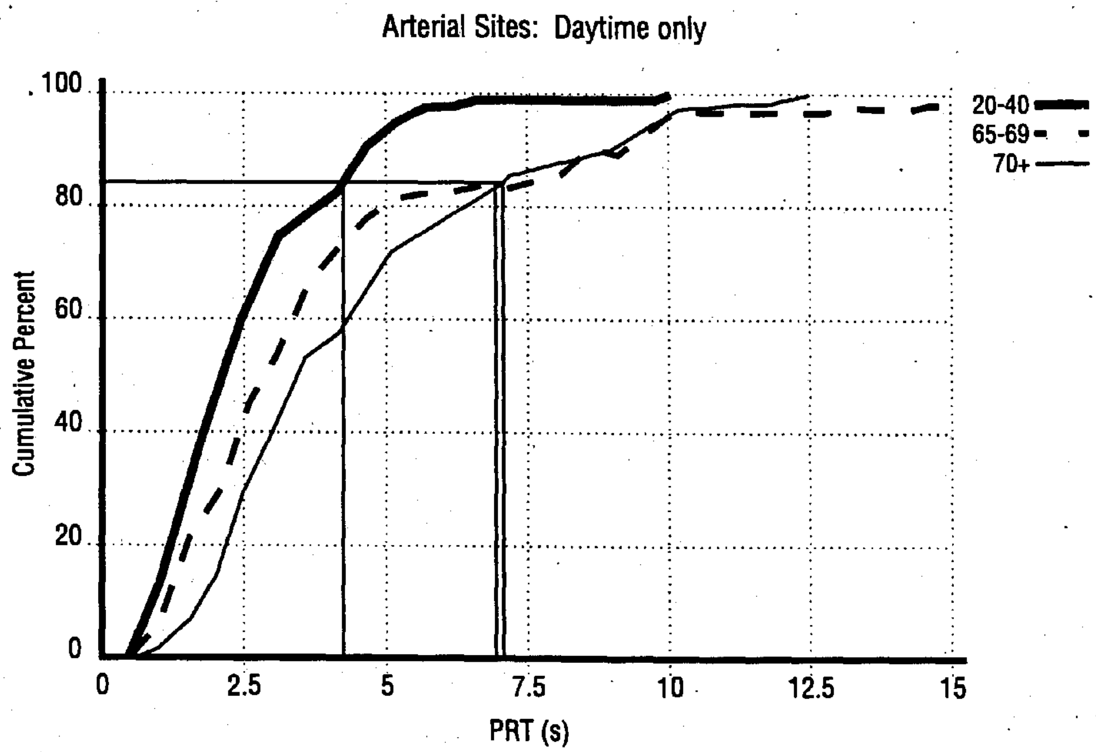


Figure 8. Freeway PRT.
(85th-percentile points included in the figure.)



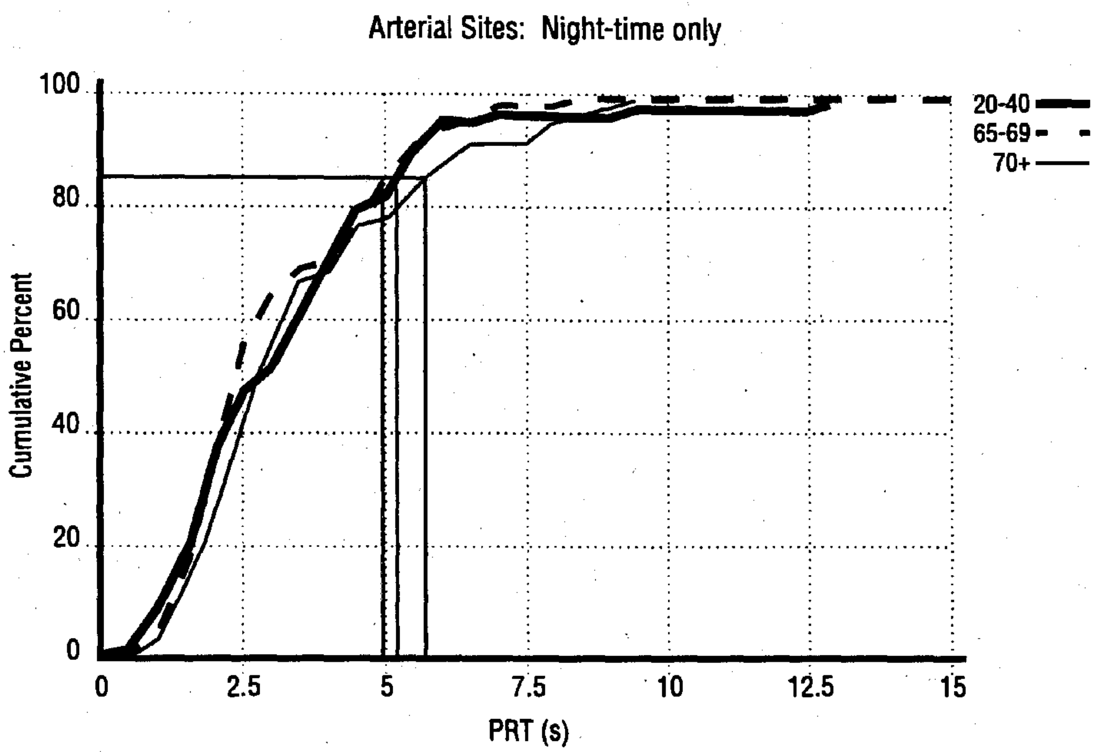


Figure 9. Arterial PRT.
(85th-percentile points included in the figure.)

Table 11. 50th- and 85th-percentile PRT by age, situation type, and day/night condition.

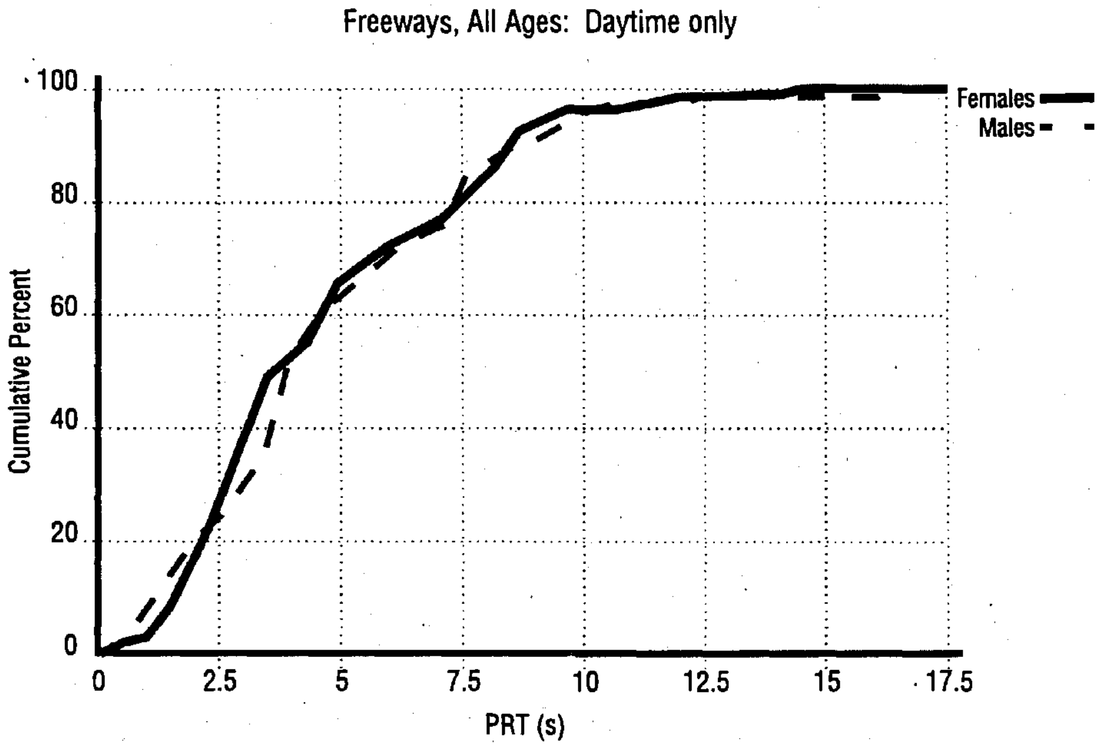
	Freeway PRT (s)				Arterial PRT (s)			
	50th %		85th %		50th %		85th %	
Age Group	Day	Night	Day	Night	Day	Night	Day	Night
20-40	2.9	3.8	7.8	7.1	2.0	2.8	4.2	5.2
65-69	3.9	3.8	7.6	6.7	2.8	2.4	7.6	4.9
70+	4.2	4.0	7.8	7.0	3.4	2.8	7.1	5.6
AASHTO			10.0				9.5	

Gender Differences. The data were examined to determine if there were any gender differences in the PRT. Figure 10 presents cumulative frequency plots of PRT values by gender for both freeway and arterial sites. These plots do not indicate any statistically significant or consistent differences between females and males in perception-reaction times. The data were further analyzed by age group and no significant gender differences were found.

Age Differences in Cues Responded To. Many of the sites had more than one cue to which subjects could respond. The first cues were often roadside warning signs, while later cues were usually pavement markings. The data were examined to see if the older and younger subjects were responding to different types of cues. Table 12 presents summaries of the types of cues (signs or pavement markings) to which the subjects responded. Occasionally, a subject would respond to a cue other than a sign or pavement marking such as site geometry, a signal head, or a parked car. These responses were classified as "Other" in the summary tables. The data reveal that during the daytime, subjects from the 70+ group were more likely to respond to pavement markings and less likely to respond to roadside traffic signs than those in the 65-to-69 and 20-to-40 groups. The 70+ drivers exhibited this tendency at seven of the eight sites where both signs and pavement markings were present. There was little difference between the 65-to-69 and 20-to-40 groups in this respect.

During the nighttime, the 70+ subjects displayed this same tendency at seven of the eight sites. What is interesting is that the 65-to-69 subjects who had displayed an equal or greater tendency than the 20-to-40 subjects to respond to signs during the daytime were less likely to respond to signs and more likely to respond to pavement markings at seven of the eight sites during the nighttime.

Maneuver Times. The average maneuver times (i.e., the time taken to initiate and complete a maneuver) are presented for each site in table 13. Again, the shaded cells indicate that there is a statistically significant difference (using a t-test) between that value and the corresponding value for the 20 to 40 age group at a 95-percent confidence level. For the daytime, average maneuver times were higher for one or both of the older age groups at 9 of



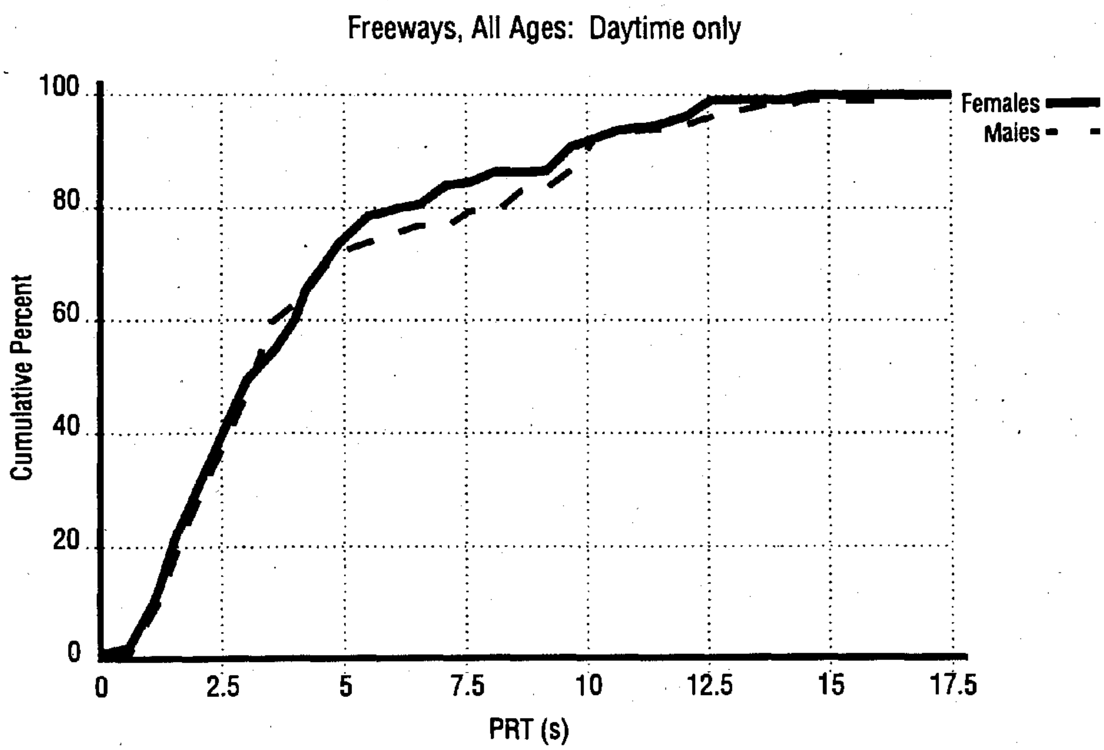


Figure 10. Gender differences.

Table 12. Cues responded to by age group and day/night condition.

Site	Age Group	Day n	Day Signs	Day Lane Markings	Day Other	Night n	Night Signs	Night Lane Markings	Night Other
1. Freeway Lane Drop	20-40	10	90%	10%	0%	11	82%	18%	0%
	65-69	15	93%	7%	0%	13	85%	15%	0%
	70+	14	71%	22%	7%	8	88%	12%	0%
2. Freeway Lane Drop	20-40	12	67%	33%	0%	12	50%	50%	0%
	65-69	13	77%	23%	0%	12	42%	58%	0%
	70+	21	43%	57%	0%	11	36%	64%	0%
3. Arterial Turn Lane	20-40	13	0%	0%	100%	4	0%	0%	100%
	65-69	15	0%	0%	100%	4	0%	0%	100%
	70+	21	0%	0%	100%	4	0%	0%	100%
4. Arterial Turn Lane	20-40	12	50%	50%	0%	12	58%	42%	0%
	65-69	14	57%	43%	0%	13	46%	54%	0%
	70+	18	44%	50%	6%	9	11%	78%	11%
5. ArterialTurn Lane	20-40	14	7%	93%	0%	14	50%	50%	0%
	65-69	16	19%	81%	0%	15	13%	87%	0%
	70+	20	15%	85%	0%	12	0%	100%	0%
6. Complex Intersection	20-40	13	0%	100%	0%	14	14%	86%	0%
	65-69	13	0%	100%	0%	13	0%	100%	0%
	70+	17	0%	100%	0%	13	0%	100%	0%
7. Freeway Lane Drop	20-40	11	36%	64%	0%	11	55%	45%	0%
	65-69	12	33%	67%	0%	9	22%	78%	0%
	70+	18	22%	78%	0%	11	9%	91%	0%
8. Freeway Lane Drop	20-40	10	60%	40%	0%	12	75%	25%	0%
	65-69	11	64%	36%	0%	9	56%	44%	0%
	70+	14	50%	42%	8%	10	50%	40%	10%
9. Freeway Lane Drop	20-40	6	83%	17%	0%	10	70%	30%	0%
	65-69	8	75%	25%	0%	9	67%	33%	0%
	70+	15	47%	47%	6%	4	25%	50%	25%
11. Arterial Turn Lane	20-40	13	69%	31%	0%	13	85%	15%	0%
	65-69	13	62%	38%	0%	15	60%	40%	0%
	70+	18	56%	44%	0%	11	36%	64%	0%
12. Arterial Turn Lane	20-40	11	0%	90%	10%	12	33%	67%	0%
	65-69	14	0%	93%	7%	15	7%	93%	0%
	70+	14	0%	79%	21%	12	8%	92%	0%

the 11 sites. However, the only statistically significant difference was at site 11 (arterial turn lane), where the younger group had a higher mean maneuver time than the older groups. For the nighttime, average maneuver times were higher for one or both of the older groups at all but site 2 (freeway lane drop), but none of the differences was statistically significant. In 2/3 of the cases, average nighttime maneuver times were shorter than the daytime values. This was probably due to the lighter traffic encountered during the night. It can be seen from table 13 that there were some fairly large differences in maneuver times that were nonetheless not statistically significant. This is a reflection of the fact that there were fairly large variances in the maneuver times. Since making a lane change was dependent not only on driver performance but also on traffic conditions and the presence of vehicles in adjacent lanes, maneuver times tended to vary widely even within a given site.

Table 13. Mean maneuver times by site, age, and day/night condition.

	Day Maneuver (s)			Night Maneuver (s)		
	Age Group			Age Group		
Site	20-40	65-69	70+	20-40	65-69	70+
1. Freeway Lane Drop	6.31	8.14	8.82	7.83	6.78	8.76
2. Freeway Lane Drop	7.63	8.45	7.12	8.91	8.21	6.34
3. Arterial Turn Lane	4.83	5.27	5.79	2.09	3.04	3.87
4. Arterial Turn Lane	11.22	11.63	11.41	11.31	11.06	12.81
5. Arterial Turn Lane	6.14	6.57	7.13	5.75	6.22	7.55
6. Complex Intersection	6.30	5.59	8.09	6.28	6.84	7.85
7. Freeway Lane Drop	6.75	7.07	8.25	6.23	7.71	6.38
8. Freeway Lane Drop	5.26	9.16	5.82	5.76	5.37	6.75
9. Freeway Lane Drop	9.43	9.56	10.20	8.64	9.76	8.42
11. Arterial Turn Lane	8.38	6.12	5.95	7.19	5.85	7.92
12. Arterial Turn Lane	8.29	7.80	7.45	5.54	6.14	6.44

The maneuver times used to compute the AASHTO DSD values include only the time required to actually perform a maneuver and do not include the pre-maneuver time required to find an appropriate gap in traffic. Because of the experimental imprecision involved in determining when the pre-maneuver and maneuver times begin and end, it is more useful to compare the total times required for detection, decision, and maneuver with the total times recommended by AASHTO. Again, the site data were combined into freeway and arterial situations. The 50th- and 85th-percentile total times (PRT + maneuver) are summarized in table 14.[10]

Looking at the 85th-percentile values, daytime total times were higher than nighttime total times in every case. The following discussion will therefore focus on the daytime values. For the freeway sites, the older groups displayed longer total times (17.6 and 18.8 s) than the younger group (16.5 s). Given that there was little difference among the three groups in the 85th-percentile PRT, the data indicate that the younger subjects in general performed maneuvers more quickly than the older subjects. At the arterial sites, the younger group again displayed a shorter 85th-percentile total time (14.1 s) than the older groups. The total times were similar (16.2 and 16.0 s) for the two older groups.

Table 14. 50th- and 85th-percentile total times (PRT + maneuver) by age and situation type.

	Freeway Total Times (s)				Arterial Total Times (s)			
	50th %		85th %		50th %		85th %	
Age Group	Day	Night	Day	Night	Day	Night	Day	Night
20-40	9.0	10.5	16.5	15.5	8.4	8.5	14.1	13.8
65-69	12.0	11.0	17.6	16.6	8.8	9.2	16.2	14.2
70+	11.8	9.8	18.8	16.5	10.5	10.1	16.0	15.4
AASHTO			14.5				14.0	

The 1990 AASHTO Green Book DSD values assume total PRT and maneuver times of 14.5 s for freeways and 14.0 s for arterials. It can be seen from table 13 that the 85th-percentile total times exceeded the recommended AASHTO values for all age groups for both freeway and arterial situations. The original AASHTO DSD work, however, assumed essentially free-flow traffic conditions in which drivers did not have to wait for gaps in traffic in order to change lanes. The runs for this experiment were conducted for the most part over heavily traveled urban freeways and arterials and subjects often had to wait for gaps in traffic before performing a lane change. This led to significantly higher maneuver times than were assumed in AASHTO. Whether this indicates a need to change the current AASHTO standards is discussed in chapter 4.[10]

Discussion. Based on the complexity of the situations that meet the DSD criteria, older drivers could be expected to show longer PRT at DSD sites. This was in fact the trend, even though for individual sites, the variability among driver response times usually precluded age differences from being statistically significant. However, while these age differences were more evident at the 50th percentile, there was very little difference among groups in the 85th-percentile PRT. Furthermore, the 85th-percentile PRT for all age groups were well within the AASHTO values, for both freeway and arterial sites. Thus based on consideration of PRT only, the AASHTO values do not appear inappropriate for older drivers.[10]

When the total time to recognize a situation and accomplish the required maneuver is considered (PRT plus maneuver time), older drivers showed somewhat longer times at both the 50th- and 85th-percentile values. The observed 85th-percentile times exceeded the AASHTO values for both freeway and arterial situations. However, this difference is due to the longer maneuver times recorded in the experiment, rather than PRT effects. Since the AASHTO model is based on free-flow conditions, longer maneuver times are to be expected under actual operational conditions on heavily traveled roadways. Since there was normally ample time to make a maneuver, the observed times reflect what drivers did, and not what they may have been capable of doing. Since there was often little urgency to make the maneuver, drivers could take whatever time they needed. Thus it is not clear whether the 85th-percentile total times in excess of the AASHTO values constitute a problem. What is apparent, however, is that assumptions about the PRT component of this total time do not appear unrealistic for older drivers.[10]

However, the findings of the DSD PRT experiment did reveal a difference between age groups that may be of significance. PRT was measured as the time to recognize and interpret the implication of some roadway cue, but <u>what</u> that cue was varied for different drivers. There are normally multiple cues to DSD situations, such as signs, markings, site geometry, traffic patterns, parked vehicles, signal heads, and so forth. Older drivers were less likely to report use of roadside signs as a cue, and showed more reliance on pavement markings. The importance of this is that roadside signs are usually used to provide the first warning of an upcoming hazard or complex driving situation. Pavement markings are usually placed much closer to the actual hazard or complex situation. If older drivers, particularly those 70 and older, do in fact have a tendency to rely on pavement markings rather than signs, it means they will often be alerted to upcoming situations much later than younger drivers and will have less time to respond with appropriate maneuvers.

GAP/LAG ACCEPTANCE

<u>Method</u>. The gap/lag acceptance experiment was related to the Case III intersection PRT experiment in that it concerned the situation where a stopped vehicle must enter or cross a major roadway. However, the focus here was not on decision time, but rather on what duration gaps were acceptable when planning various maneuvers (left turn, right turn, through). Thus it provided complementary data to the previous PRT experiment, as well information that may be useful for alternative models for intersection sight distance requirements.

A distinction is made in this experiment between a "gap" and a "lag." A gap is the temporal interval between two approaching vehicles. Institute of Transportation Engineers' *Traffic Engineering Handbook* defines a gap as the time interval between two successive vehicles, measured from the rear of a vehicle to the front of the following vehicle.[48] This definition was used to operationalize the measurement of temporal gaps in the present experiment, whether the two successive vehicles were approaching from the same direction (one following the other) or from opposite directions (for left or crossing maneuvers). We use the term lag to refer to the time interval from the point of the observer to the arrival of the front of the next approaching vehicle. It is important to distinguish these two situations because they represent distinct perceptual tasks. In the case of a gap, the waiting driver is making a judgment about the interval between two moving vehicles. In the case of a lag, the waiting driver is making a judgment about the arrival time of a single approaching vehicle. A particular gap may be long enough that a waiting driver might accept it as adequate to permit a desired maneuver (e.g., a right turn). However, at some point after the first vehicle defining the gap has passed, the trailing vehicle will eventually be close enough that the driver would no longer accept the remaining lag as safe enough to permit the maneuver. Thus the analysis of the data of this experiment addresses both the duration of a gap that will be accepted, and the point at which a lag would be rejected.

In this experiment, subjects did not actually execute driving maneuvers. Rather, they sat in a vehicle, perpendicular to the conflicting roadway, and made "yes" or "no" judgments about potential maneuvers. Although the vehicle was not actually located in an intersection, the subject was asked to imagine it being stopped on a typical asphalt roadway surface, awaiting the opportunity to perform a particular maneuver. The subject had a hand-held button console. The experimenter informed the subject what the desired traffic maneuver was to be: turn left, turn right, or through. The subject's task was to hold the button in the depressed position whenever it would be safe to initiate that maneuver, and to release the button whenever it would be unsafe. A given intended maneuver remained in effect for 10 minutes, during which the button position provided an indication of the subject's judgments at every moment. The subject's decisions were related to traffic characteristics by means of simultaneous recording of traffic. A pair of sensors mounted in front of the vehicle recorded the presence of passing vehicles. A photoelectric sensor, aimed at a reflector across the roadway, responded to vehicles passing in either direction. A microwave sensor was adjusted to respond to vehicles in the near lane (i.e., approaching from the left) only. When processed by appropriate logic, this information permitted determination of gap durations and the direction of travel of the crossing vehicles. Since the subject's button responses were simultaneously recorded by the same data collection system, responses could be related to gap characteristics. Passing traffic was also filmed by a roof-mounted array of video cameras on the study vehicle. This provided a 180-field of view and the video records were used to confirm and edit data as recorded by the sensors. The roof-mounted cameras were concealed in a modified cargo carrier, so as not to influence the behavior of passing drivers.

The test vehicle was a Chevrolet Astro minivan, selected because it provided excellent front-seat visibility, permitting two subjects to be tested at the same time (left or right seat position had no effect on the judgments). The van housed all control and data collection equipment and power supplies.

Each session consisted of about 10 minutes of data collection for each of the three maneuvers (left turn, right turn, through). Each subject took part in separate sessions at each of the two sites included in the study. Each site was located far enough from traffic signals so that passing traffic was not characterized by heavy platooning. The "low-speed" site was on a 30 mi/h (48 km/h), two-lane undivided suburban arterial with residences, doctors offices, churches, etc. The "high-speed" site was on a 50 mi/h (81 km/h), two-lane undivided rural roadway with occasional homes and commercial driveways. Both daytime and nighttime sessions were conducted during non-peak traffic periods. The high-speed site was unlit at night, and the low-speed site had street lights.

The number of subjects taking part under each condition, broken out by age group, is shown in table 15. Note that the total of 138 represents the overall number of subject sessions, not 138 different individuals. Each subject participated in a session at each site (both daytime or both night), and some participated under all four conditions. Sequences were randomized to control for any possible effects of order, due to practice, fatigue, etc.

Table 15. Number of subject sessions: gap/lag acceptance experiment.

	20-40 Years Old	65-69 Years Old	70+ Years Old	TOTAL
Low-Speed: Day	F 7	F 7	F 7	F 21
	M 7	M 5	M 6	M 18
Low-Speed: Night	F 6	F 4	F 6	F 16
	M 3	M 3	M 4	M 10
High-Speed: Day	F 7	F 7	F 9	F 23
	M 8	M 4	M 5	M 17
High-Speed: Night	F 10	F 3	F 4	F 17
	M 4	M 6	M 6	M 16
TOTAL	52	39	47	138

<u>Results</u>. These data were analyzed in two ways. First, gap acceptance rates were derived for various conditions of interest. The interval between any two consecutive vehicles passing in front of the subject vehicle defined a gap. For right turns, a gap was defined only based on vehicles in the near lane; for left and through maneuvers, a vehicle in either lane could define the start or end of a gap. For each gap that a subject encountered, it was determined whether the subject indicated that it was safe to proceed at any time during that gap. This analysis yielded the proportion of gaps of any given size that were accepted by subjects. The second portion of the analysis dealt with lags. During a lag, the subject is not judging the interval between two approaching vehicles, but rather the interval between himself and the next arriving vehicle. Thus this analysis determined at what point during a relatively long, accepted gap the subject finally determined that it was no longer safe to proceed with the maneuver. The interval between the point at which a "no longer safe" decision was made, and the arrival of the next vehicle, defines the lag rejected. This can be viewed as the "safety margin" below which the subject would not initiate the maneuver. Analyses of these lag rejection points were based only on those gaps that were accepted by the subject and that exceeded 9 s. Findings on gap acceptance will be presented first, followed by the findings on lag rejection.

Gap Acceptance. Gap acceptance findings are summarized in figures 11 through 19 and in table 16. The figures are all similar in format. The X-axis shows the size of the gap, in 2-s intervals. The Y-axis shows the percentage of gaps of a given size that were accepted. Thus for example, in figure 11, 20 percent of the gaps in the 5-to-6 s range were accepted. Small gaps are rarely accepted, and the function assumes an ogive shape as acceptance rates increase and then asymptote near 100 percent. Figure 11 presents the summary gap acceptance data collapsed across all conditions of the experiment. This figure shows that the 50-percent gap acceptance point is about 7 s; that is, if a gap is 7 s long, only about half the subjects would accept it. The 85th-percentile point is around 11 s.

Figure 12 breaks these data out by site for the daytime condition; figure 13 does the same for the night condition. Neither light condition nor site had a large effect on these functions. Figure 14 shows daytime gap acceptance as a function of the planned driving maneuver; figure 15 presents the same data for night. Again differences are not dramatic, although somewhat shorter gaps appear to be accepted for through maneuvers. The reason for the inversion in the daytime right turn function, and its apparently lower asymptote, are unknown, but are likely aberrant. Figures 16 and 17 show gender differences under day and night conditions; males accept gaps about 1 s briefer through much of the function in daytime; there is little difference at night. Figures 18 and 19 show functions for each of the three age groups, under day and night viewing conditions. A clear difference with age is apparent in daytime, but there is no consistent effect at night. Summary data is in table 16, which provides estimates of the 50-percent gap acceptance value for each age group under various experimental conditions. The 50-percent acceptance values were estimated by interpolation from percentages accepted within each 1-s bin, as shown in the figures. The mid-point of the bin (e.g., 5.5 s for the 5-to-6 s bin) was assigned the observed acceptance rate for that bin, and the 50-percent point was then estimated by interpolating between these points. Table 16 shows progressively longer gap acceptance requirements with increasing age. Collapsed across all conditions, the oldest group required about 1.1 s longer than the youngest group.

Lag Rejection. The findings on lag rejection "safety margins" are summarized in table 17. The table presents the mean gap rejection point for each age group under various experimental conditions. Across all conditions, the mean gap rejection point was 5.3 s; that is, the subject decided that it was unsafe to proceed with the maneuver when the approaching vehicle was 5.3 s away. As with the gap acceptance findings, subjects in the seventy-and-older age group required the longest times. However, for this measure, the shortest mean time was obtained for the 65-to-69-year olds. This parallels the shorter times observed for this age group in the intersection PRT experiment. Table 17 indicates that there was no consistent effect of light condition, and slightly (0.3 to 0.45) longer rejection points for the high speed site. However, there was a more influence of the type of driving maneuver: the right turn condition resulted in substantially longer times. The influence of maneuver type was most pronounced for the oldest group, where the right maneuver resulted in times 1.39 s longer than left turns and 1.69 s longer than through maneuvers.

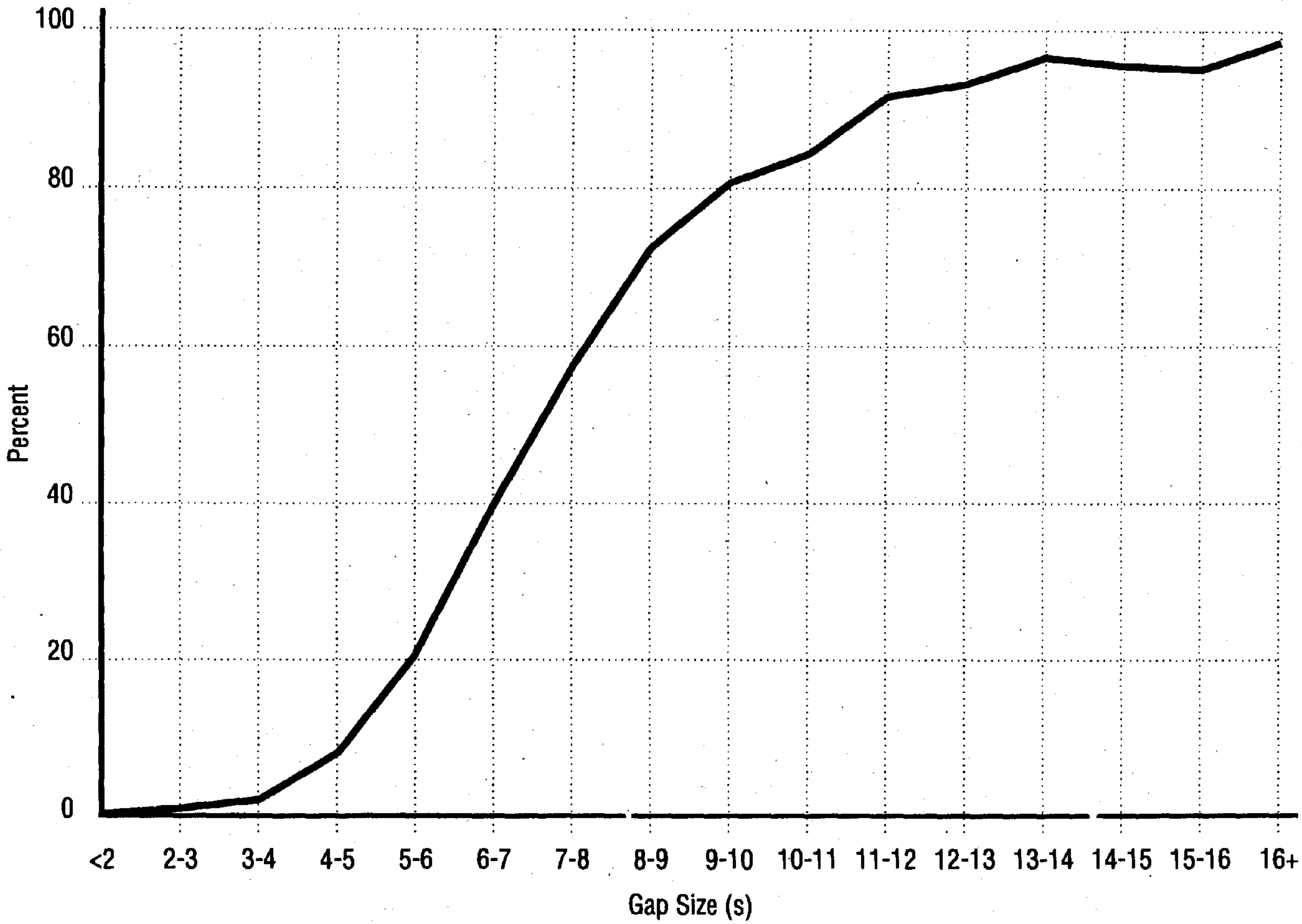


Figure 11. Percentage of gaps accepted for all subjects (day and night combined).

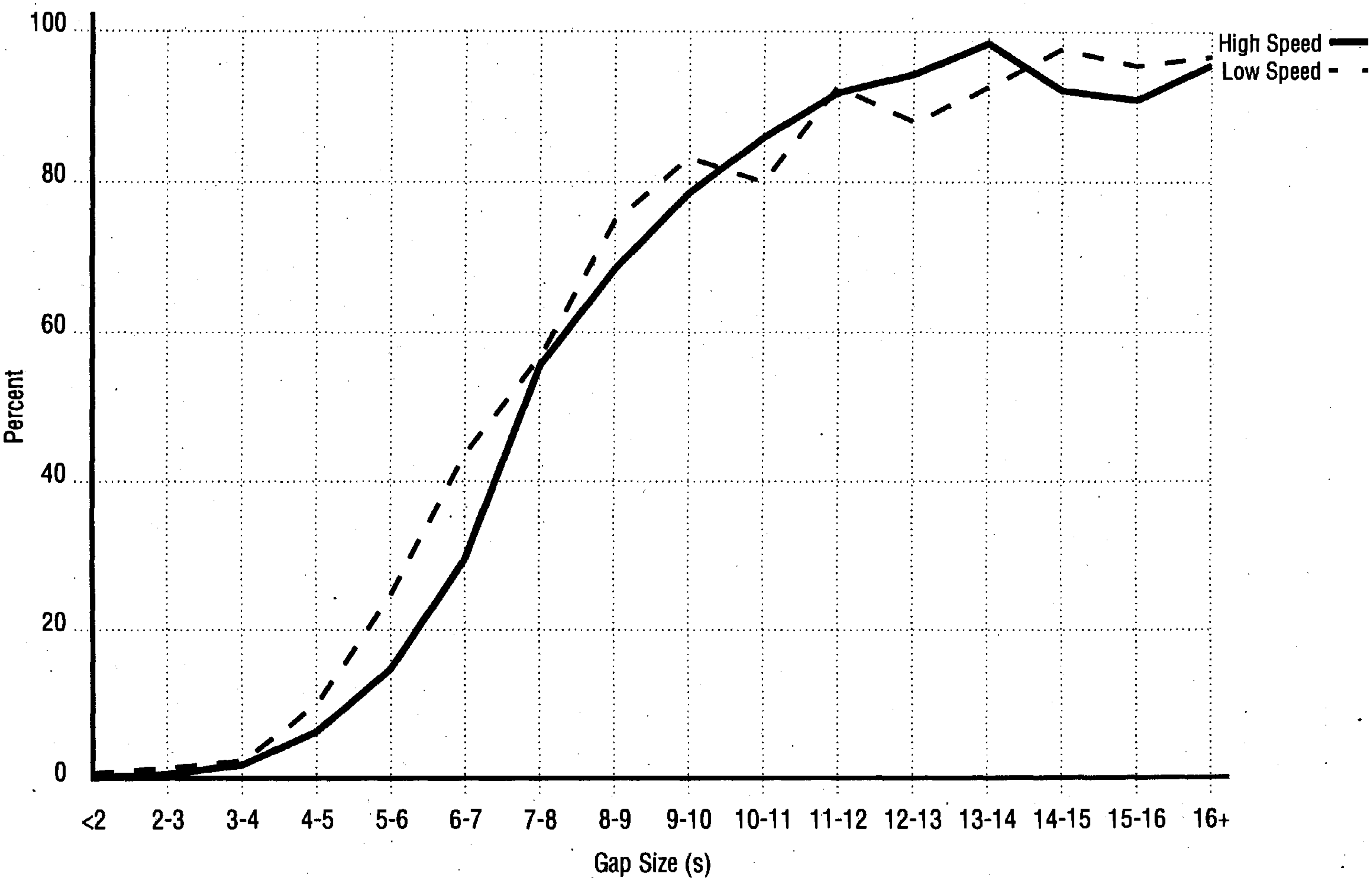


Figure 12. Percentage of gaps accepted for all subjects (day only) by site.

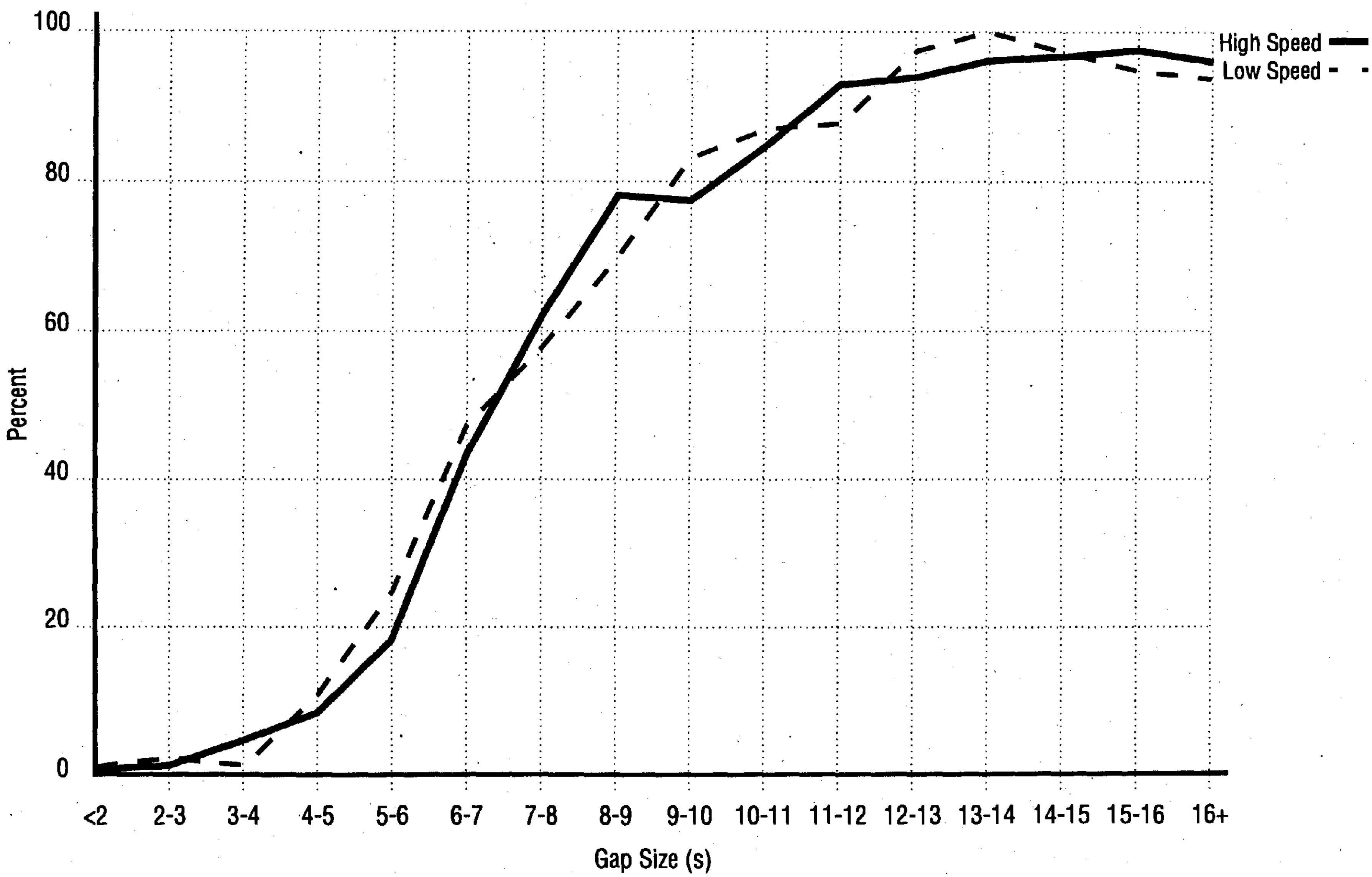


Figure 13. Percentage of gaps accepted for all subjects (night only) by site.

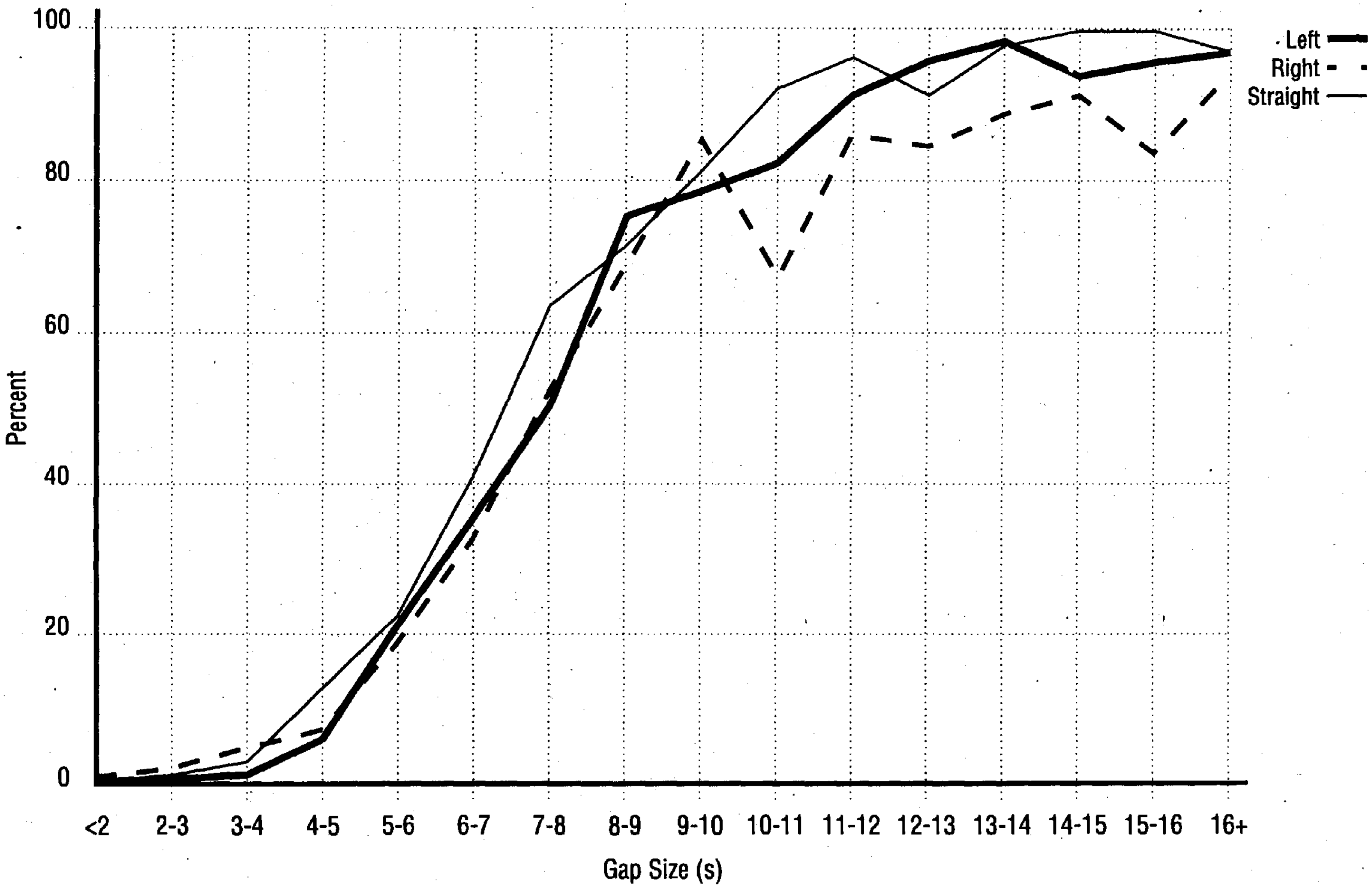


Figure 14. Percentage of gaps accepted for all subjects (day only) by maneuver.

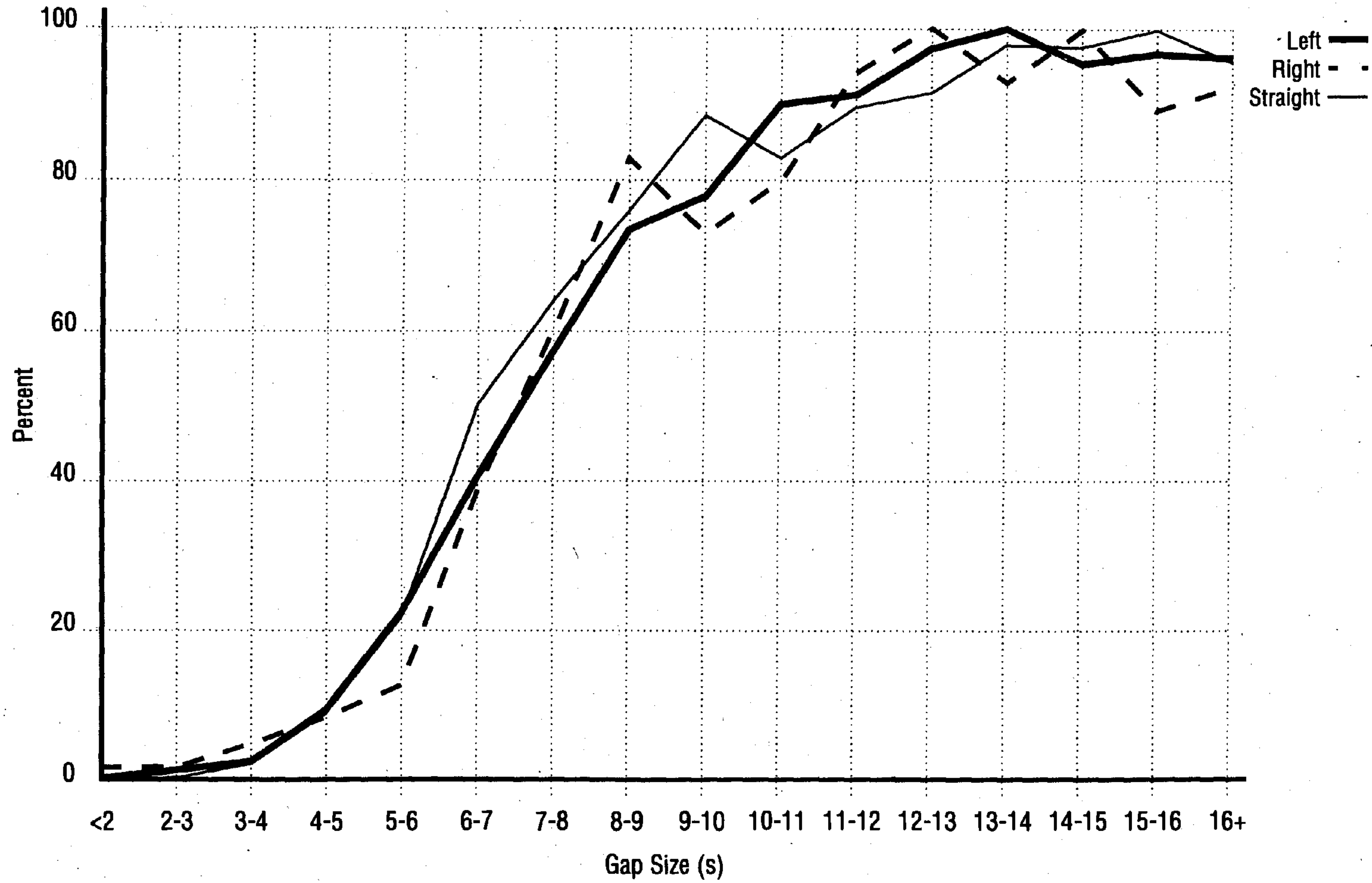


Figure 15. Percentage of gaps accepted for all subjects (night only) by maneuver.

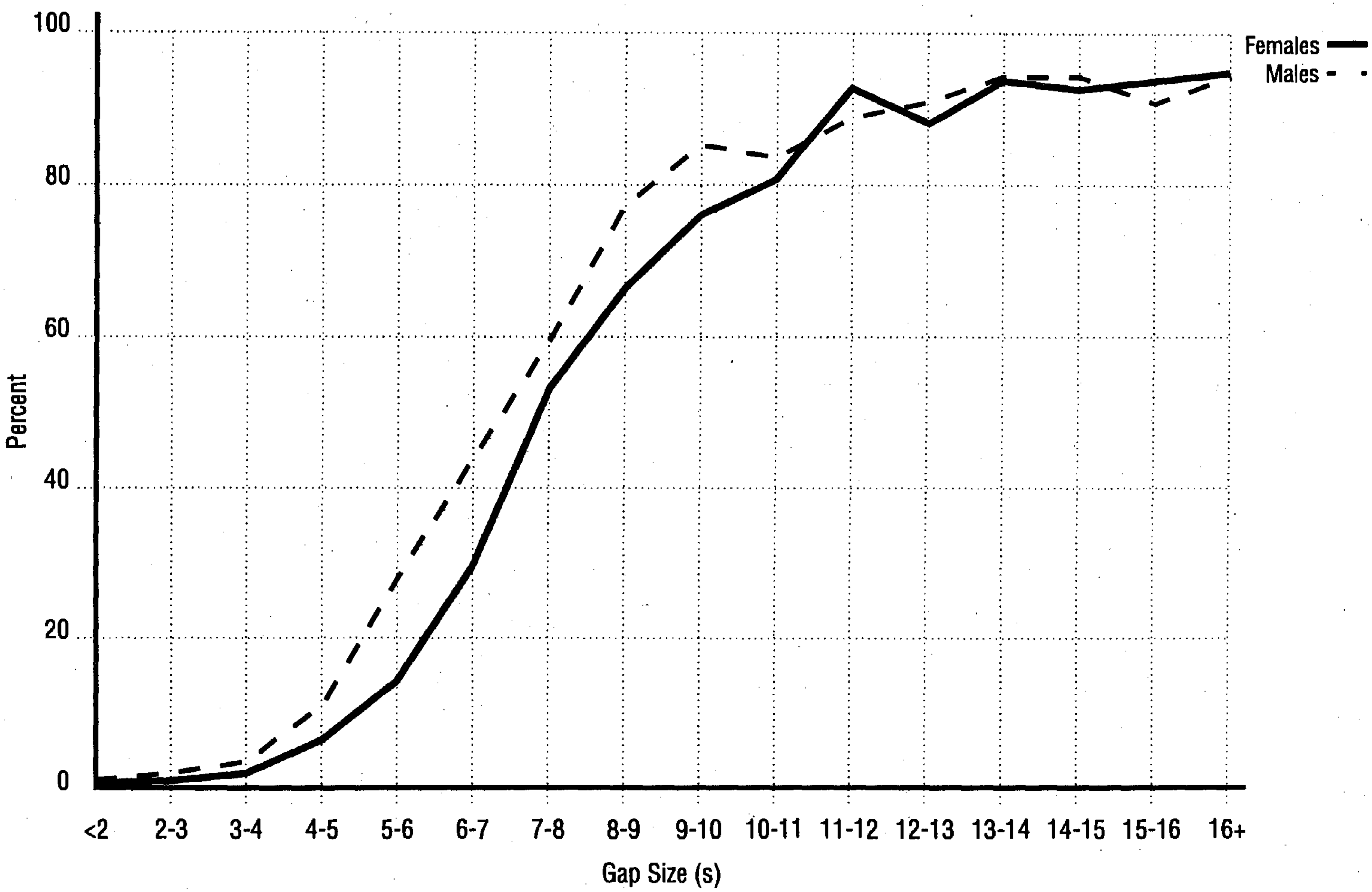


Figure 16. Percentage of gaps accepted for all subjects (day only) by gender.

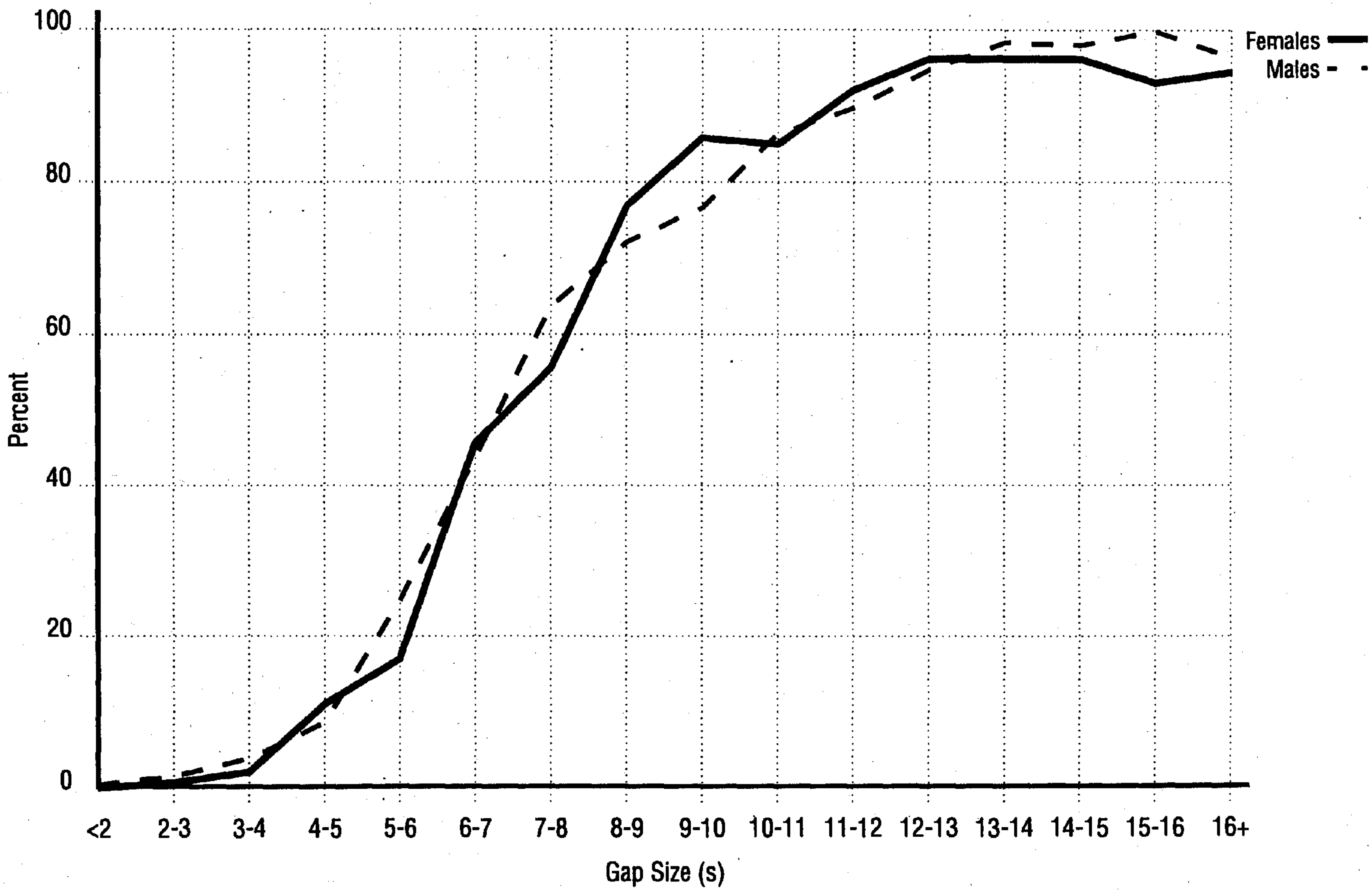


Figure 17. Percentage of gaps accepted for all subjects (night only) by gender.

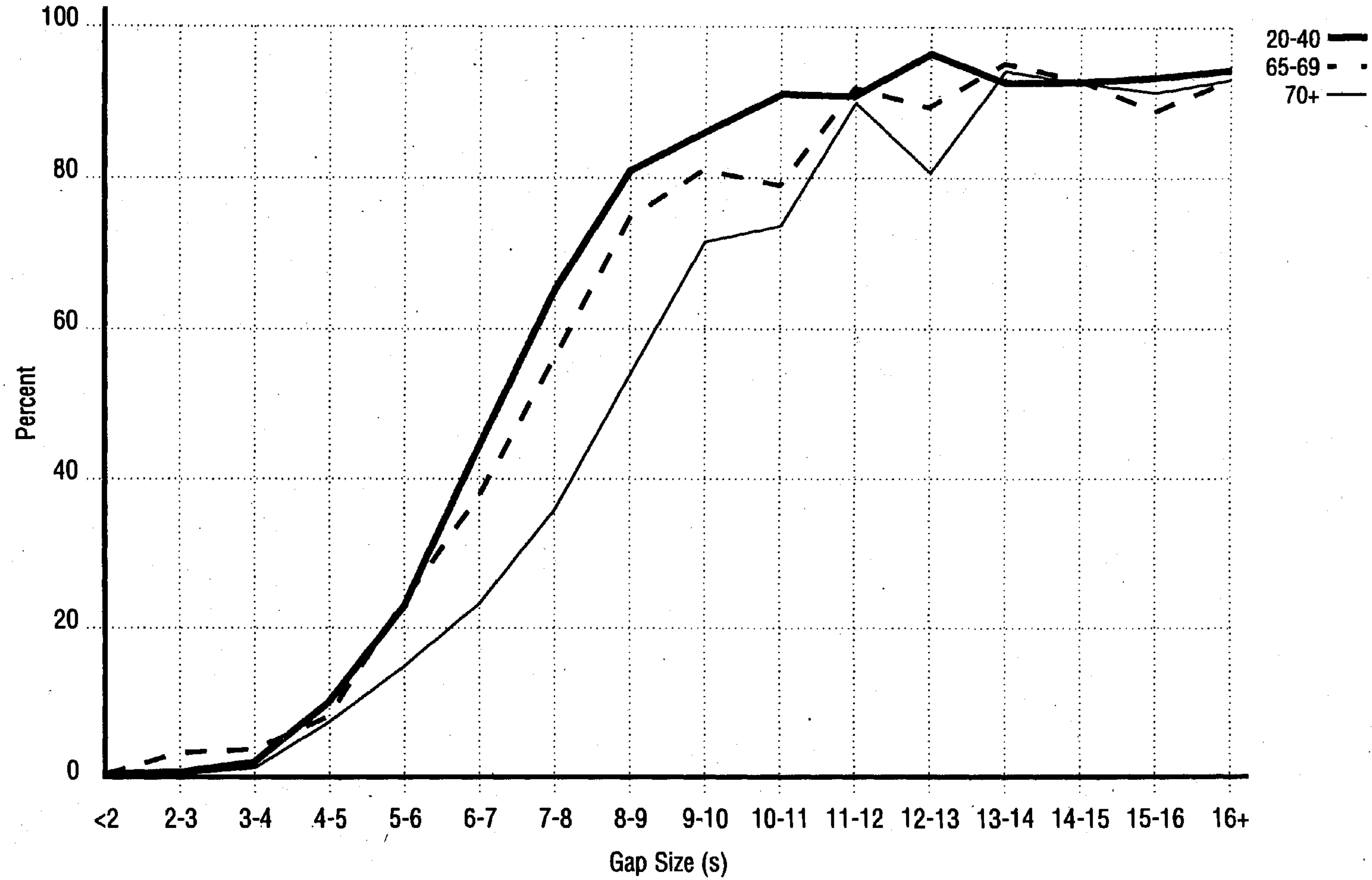


Figure 18. Percentage of gaps accepted (day only) by age group.

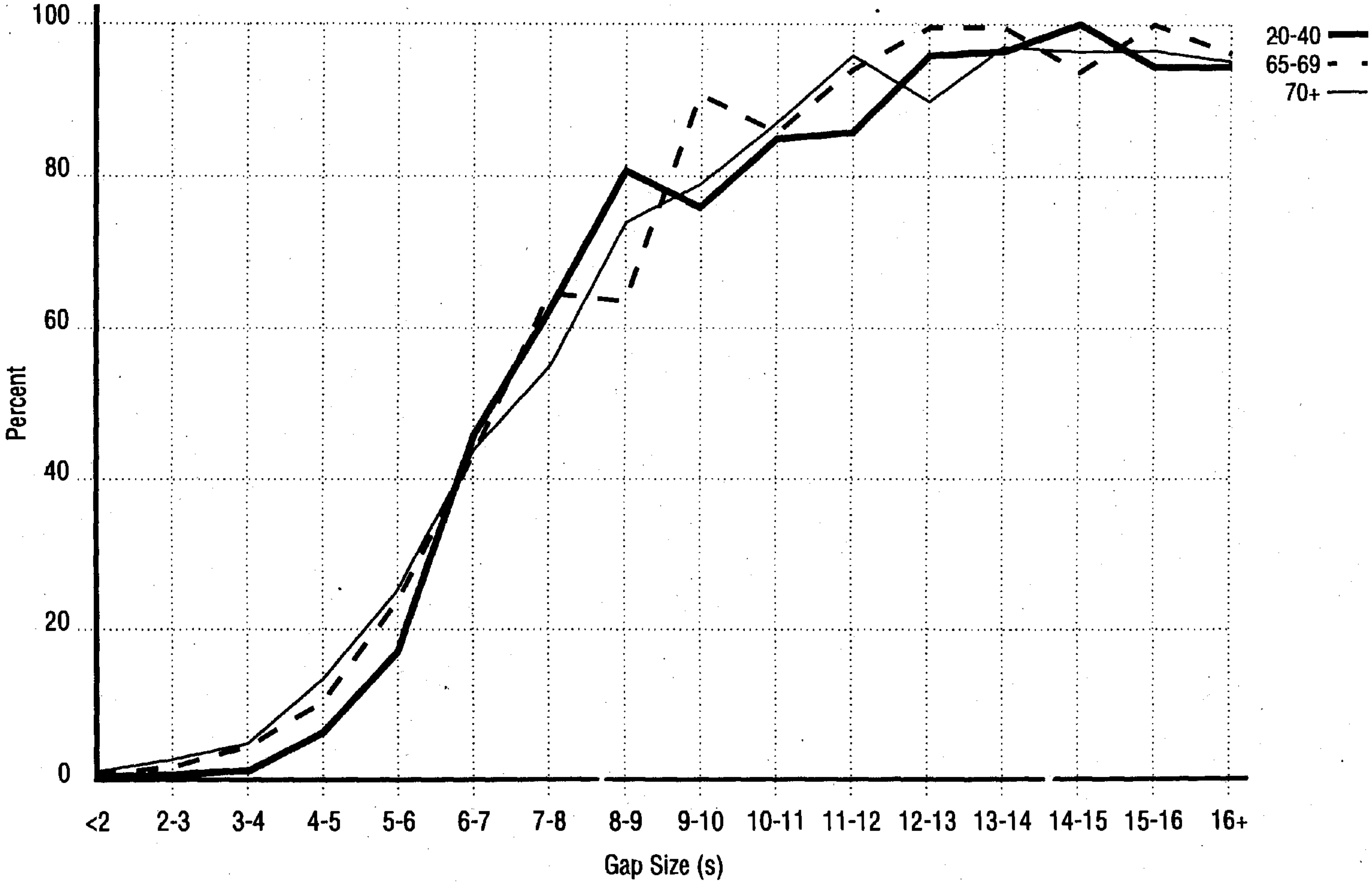


Figure 19. Percentage of gaps accepted (night only) by age group.

Table 16. Estimated 50-percent gap acceptance point (s) for various experimental conditions.

	20-40 Years Old	65-69 Years Old	70+ Years Old
Site			
High Speed	6.87	7.38	7.67
Low Speed	6.50	6.48	7.99
Light Condition			
Day	6.73	7.15	8.24
Night	6.76	6.82	7.09
Maneuver			
Left	6.84	7.63	7.99
Right	6.89	7.63	7.50
Through	6.59	6.48	7.84
All	6.74	7.06	7.85

Discussion. The findings on gap/lag acceptance did indicate that older subjects required greater gaps than younger subjects. Averaged over all conditions, the point at which 50 percent of subjects would accept a gap was just over 1 s longer for the oldest group than it was for the youngest group, with the 65-to-69-year olds falling in between. Similarly, the oldest group had a mean lag rejection point that was about a half second longer than younger subjects (although for this measure, the 65-to-69 year old group accepted shorter margins than the youngest group). These findings are in contrast to those of the Case III intersection PRT experiment, where no differences were seen between age groups in the total time required to perceive, react, and complete a maneuver, and where the young group showed the longest PRT. The Case III intersection PRT experiment measured how long it took subject drivers to perceive, react, and make a maneuver, given that there was an adequate gap. The gap/lag acceptance experiment asked what duration gaps drivers would be willing to accept as adequate. The longer times required by older subjects in the gap/lag acceptance study may thus be reflecting different decision criteria, with the older driver showing more caution. It could also in part reflect the slightly longer maneuver times observed for older drivers in the earlier experiment, although this was only on the order of about a fifth of a second.

Table 17. Mean lag rejection point ("safety margin," in s).
for various experimental conditions.

	20-40 Years Old	65-69 Years Old	70+ Years Old
Site			
High Speed	5.47	4.83	6.04
Low Speed	5.07	4.54	5.63
Light Condition			
Day	5.22	4.71	6.00
Night	5.44	4.64	5.66
Maneuver			
Left	5.21	4.65	5.51
Right	5.90	5.12	6.90
Through	4.87	4.28	5.21
All	5.32	4.69	5.86

Age differences in gap acceptance were not uniform across all conditions. While the typical difference between the youngest and oldest groups was about 1.2 s for all three driving maneuvers (left turn, right turn, through), the difference was more pronounced for daytime conditions (1.5 s) and the lower speed site (1.5 s). The reason for the diminished age differences at night is not certain. Comparison of figures 18 and 19 indicates that the major difference is in the shift of the function for older subjects at night. The oldest group was more conservative in daytime than at night, while there was little change for younger drivers.

Subjects were willing to accept a briefer temporal margin for rejection of a lag than for acceptance of a gap. That is, on the average, during a lag a subject was willing to execute the maneuver until the approaching vehicle was only 5.3 s away. In contrast, gaps 5 to 6 s long were rejected about 80 percent of the time; the 50-percent gap acceptance point was about 7.1 s. There are a number of possible reasons for this difference, such as the relative difficulty of the different perceptual judgments involved, the need to allow some margin of error for the arrival of the first vehicle defining the gap, etc. In any case, drivers appear to demand more time when executing a maneuver in the gap between two vehicles than during the lag before a single approaching vehicle. It may be noted that the research literature on "gap acceptance" often uses the term generally, to refer to either gaps or lags. The present findings indicate the importance of distinguishing between these situations, since driver decision making is clearly different. The specific gap and lag acceptance values obtained in this experiment are similar to those obtained in some observational studies of actual traffic; this is discussed further in chapter 5. However, it should be noted that there has been a range of findings obtained in such experiments, owing to the importance of such factors as site and traffic characteristics, definitions, recording techniques, and analytic methods.[49]

Since the intersection PRT experiment and the gap/lag acceptance experiment used different sites the findings are not formally comparable. However, the general temporal aspects of driver behavior can be compared. Across all conditions, the gap duration accepted about 50 percent of the time was found to be 7.1 s. This value is slightly longer than the 6.7 s total time (PRT plus maneuver) observed in the PRT experiment. The difference was somewhat more pronounced at the 85th percentile values (8.1 s in the PRT experiment, 10.6 s for gap acceptance). The difference may reflect a margin of safety drivers allow beyond the time it normally takes to execute a maneuver. The mean point of lag rejection in the gap acceptance experiment was 5.3 s, the same as the mean time observed for execution of the maneuver in the PRT experiment.

CHAPTER 4. IMPLICATIONS FOR CHANGES TO SIGHT DISTANCE EQUATIONS

INTERSECTION SIGHT DISTANCE

As a geometric design element, intersection sight distance is intended to provide the driver of a vehicle approaching an at-grade intersection with an unobstructed view of the entire intersection and views of sufficient lengths of the intersecting highway to permit control of the vehicle to avoid collisions. Sight distance at a crossroad or street should be sufficient along the predominant highway to avoid the hazard of collision between a vehicle starting to cross the highway from a stop position and a vehicle on the through highway operating at the design speed and appearing after the crossing movement has begun. AASHTO's Green Book defines four types of ISD standards depending on the type of control present at an intersection: (I) no control, (II) yield control, (III) stop control, and (IV) signal control. The focus of the experimental study was on the performance of drivers at Case III stop controlled intersections. In these types of situations, drivers stopped at an intersection may either cross the intersecting roadway (Case IIIA), turn left (Case IIIB), or turn right (Case IIIC).[10]

Case IIIA - Crossing Maneuver. The general formula for computing intersection sight distance for a simple crossing maneuver is:

$$d = 1.47V(J + t_a) \tag{3}$$

where V equals the design speed for the major highway in miles per hour, J equals the sum of the perception-reaction time and the time required to set the vehicle in motion (in seconds), and t_a equals the time in seconds required to accelerate and traverse the major highway pavement. The value for J, which is the primary concern here, is assumed by AASHTO to equal 2.0 s.

The median and 85th-percentile J values measured at all 14 sites in the Case III intersection PRT experiment are presented in table 18. There were three sites which involved crossing maneuvers: sites 1, 10, and 12. It can be seen that the 85th-percentile J value at site 1 (2.35 s) exceeded the AASHTO standard of 2.0 s by 18 percent. The 85th-percentile values for sites 10 and 12 were at or below the AASHTO standard. It can further be seen from table 18 that the 85th-percentile J values exceeded the AASHTO 2.0-s design standard at 7 of the 14 sites. This would seem to indicate that the current standard may be insufficient to accommodate all drivers or all turning situations and may need to be revised. However, the experimental procedure should be examined first.

The experimental procedure required that the subjects, once stopped at an intersection, look down at a display and wait until they received an "OK to proceed" signal from the experimenter. This action completely diverted the subject's attention away from the intersection and required the subjects to "re-orient" themselves once the signal to proceed was given. This really represents a worst-case scenario for visual searching. In the real world, drivers would likely begin their visual search for vehicles/gaps as they approached the intersection rather than performing the driving/search tasks sequentially (i.e., slow vehicle upon approach -- stop vehicle -- begin search). One would therefore expect that the J values obtained in the experiment presented here would be slightly longer than those one would find in everyday driving practice.

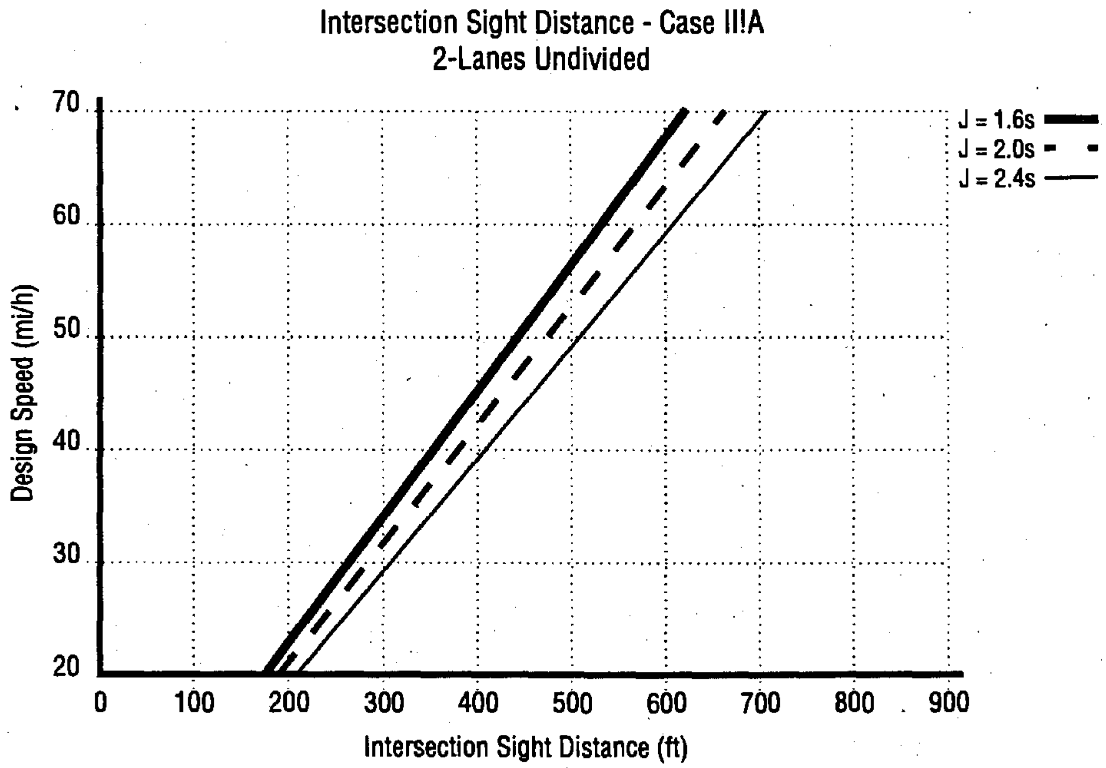
Table 18. Case III J values.

Site	Maneuver Type	Geometry (Lanes/Type)	Speed mi/h (km/h)**	Median J (s)	85th % J (s)
1	Through	4-Divided	55 (89)	1.81	2.35
2	Left	4-Divided	55 (89)	1.51	2.10
3	Left*	2-Undivided	45 (72)	1.65	2.40
4	Right*	2-Undivided	45 (72)	1.48	2.15
5	Left	4-Divided	55 (89)	1.49	2.25
6	Right	4-Divided	55 (89)	1.49	2.12
7	Right	2-Undivided	35 (56)	1.20	1.75
8	Left	2-Undivided	35 (56)	1.14	1.70
9	Left*	2-Undivided	25 (40)	1.37	1.80
10	Through	2-Undivided	25 (40)	1.20	1.60
11	Right*	2-Undivided	25 (40)	1.39	1.90
12	Through	2-Undivided	40 (65)	1.49	1.95
13	Left	2-Undivided	35 (56)	1.11	1.88
14	Right	2-Undivided	40 (65)	1.61	2.17

* - Maneuver made at a skewed intersection.
** - mi = km x 0.621

Even so, it could be argued that using a worst-case scenario to represent the slowest drivers may be desirable from a safety standpoint. Therefore, the impacts of increasing the AASHTO J value on Case IIIA intersection sight distance standards were examined. The fastest and slowest 85th-percentile J values recorded for *all* 14 sites (1.60 and 2.40 s, respectively) were used to recompute figure IX-39, "Sight Distance at Intersections - Case IIIA" from the 1990 Green Book for 2-lane undivided and 4-lane undivided cross-sections.[10] These graphs are shown in figure 20. To illustrate, the net changes in ISD for the two-lane undivided situation are summarized in table 19.

Each change in J of 0.1 s results in an approximate 1.5 percent change in Case IIIA intersection sight distance. This percentage change is the same for all cross-section types. An examination of the table reveals that for a 2-lane undivided cross section, an increase in J of 0.4 s would translate into an increase in ISD of 29 ft (9 m) or approximately one car length for a 50 mi/h (81 km/h) design speed.



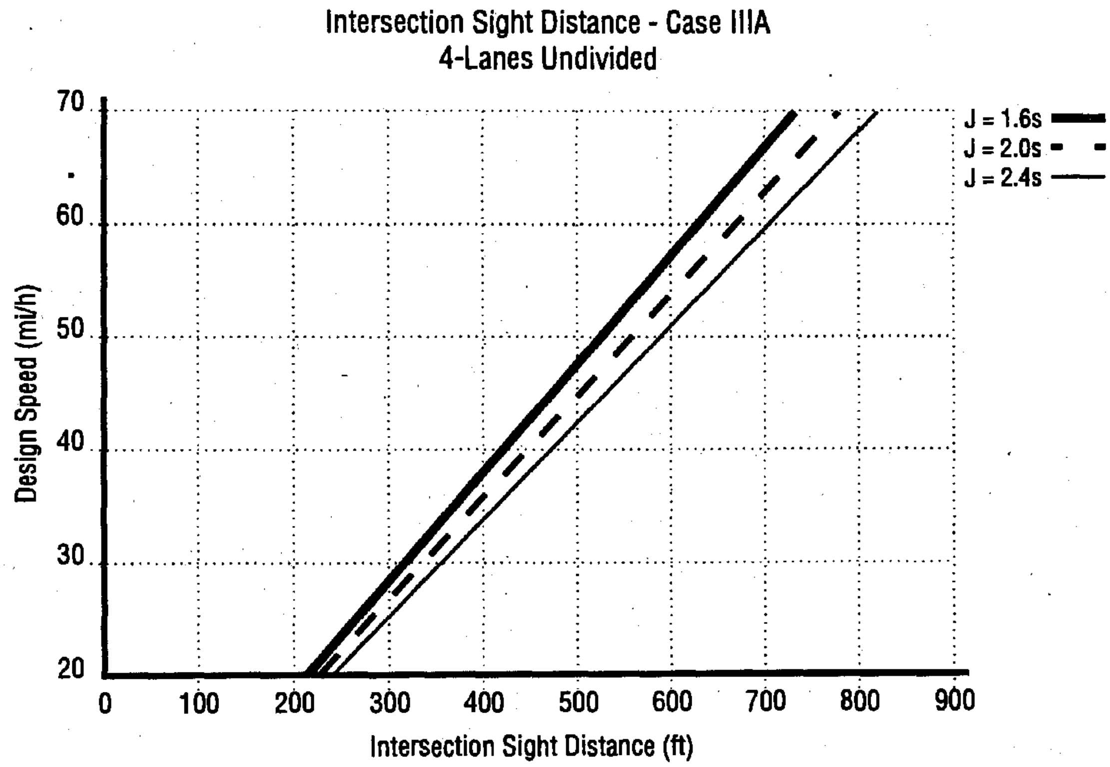


Figure 20. Intersection sight distance for Case IIIA.

Table 19. Change in Case IIIA Intersection sight distance (ft/m) for change in J:

Design Speed mi/h (km/h)*	ISD [ft (m)]* 2-lane undivided	Δ J (s) 0.1	0.2	0.3	0.4
20 (32)	191 (58)	3 (1.5%)	6 (3.1%)	9 (4.6%)	12 (6.2%)
30 (48)	287 (88)	4	9	13	18
40 (65)	382 (117)	6	12	18	24
50 (81)	478 (146)	7	15	22	29
60 (97)	573 (175)	9	18	26	35
70 (113)	669 (204)	10	21	31	41

*mi = km x 0.621, ft = m x 3.28

The total crossing times for these situations were also examined to verify the AASHTO standards. Of the three "crossing" sites, only sites 10 and 12 could be used for comparison. Site 1 had the subjects stop in the median of a 4-lane divided highway (AASHTO assumes continuous acceleration across the roadway) and therefore could not be used. For the site 10 geometrics, AASHTO specifies $J = 2.0$ s and $t_a = 4.5$ s, for a total crossing time of 6.5 s. The 85th-percentile total crossing time measured in our experiment was 6.4 s. For site 12, AASHTO specifies $J = 2.0$ s and $t_a = 5.7$ s, for a total crossing time of 7.7 s. The 85th-percentile total crossing time was 7.4 s. Both values agree with the AASHTO standard.

Case IIIB & IIIC - Turning Maneuvers. For left-turning vehicles, there must be sufficient sight distance to the left to allow the vehicle to cross the near lanes without interfering with oncoming traffic. This distance is computed using the same formula used for Case IIIA maneuvers, $d = 1.47V(J + t_a)$. There must also be sufficient sight distance to the right to allow the vehicle to turn left and accelerate to 85 percent of the design speed without being overtaken by a vehicle coming from the right (this is referred to as the Case IIIB-2b sight distance in AASHTO). This right-side sight distance will in almost all cases be much greater than the required left-side sight distance. Similarly, for right-turning vehicles, the left-side sight distance must be sufficient to allow the vehicle to turn right and accelerate to 85 percent of the design speed without being overtaken by a vehicle coming from the left (this is referred to a the Case IIICb sight distance). The computations for the B2-b and Cb sight distances are considerably more involved than for the Case IIIA sight distances, but the critical factor is the time required for a vehicle to accelerate to 85 percent of the design speed.[10] The B-2b and Cb sight distances normally differ by only a few feet for any given design speed and for all practical purposes may be considered equivalent.

From this experiment, the 85th-percentile J values exceeded the AASHTO 2.0 s standard at 6 of the 11 sites where turning maneuvers were performed. The highest value was 2.4 s and the lowest was 1.7 s. As with the crossing maneuver, the impact of increasing the J value on the required Case IIIB & IIIC intersection site distances was therefore examined.

Figure IX-40 in AASHTO presents ISD curves for Case IIIB & IIIC maneuvers.[10] The B-2b & Cb curve represents the minimum required right-side sight distance for left turns and left-side sight distance for right turns. Since it represents the longest sight distances, the B-2b and Cb ISD curve was recomputed to reflect changes in the assumed J value. The results are sum-marized in the table 20. An increase in J of 0.1 s will result in a 0.8 percent to 1.3 percent increase in the required ISD, depending on the design speed. For the worst-case scenario of J = 2.4 s, this translates into an extra 30 ft (9 m) of sight distance for a 50 mi/h (81 km/h) design speed. This difference is relatively small compared to the current standard of 850 ft (259 m) because sight distance for turning maneuvers is dependent primarily on the time required to accelerate to design speed, not J.

Table 20. Change in Case IIIB-2b & Cb ISD (ft/m) for changes in J.

Design Speed mi/h (km/h)*	AASHTO ISD ft (m)*	Δ J (s)			
		0.1	0.2	0.3	0.4
20 (32)	240 (73)	3	6	9	12
25 (40)	315 (96)	4	7	11	15
30 (48)	385 (117)	4	9	13	18
35 (56)	495 (151)	5	10	16	21
40 (65)	600 (183)	6	12	18	24
45 (72)	720 (220)	7	13	20	27
50 (81)	850 (259)	7	15	22	30
55 (89)	1000 (305)	8	16	25	33
60 (97)	1165 (355)	9	18	27	36

*mi = km x 0.621, ft = m x 3.28

<u>Conclusions</u>. The 85th-percentile J values approximate the 2.0-s AASHTO standard at all of the sites. While some values were higher, none was more than 20 percent higher, and others were as much as 20 percent lower. Given that the experimental design represented a worst-case scenario for visual search and detection, it is possible the measured values were slightly higher than one would expect to find under "normal" driving conditions. Furthermore, a change in J of a few tenths of a second would produce relatively minor increases in both Case IIIA and Case IIIB & C sight distances. For these reasons, it is not felt that any changes to the current standards are required. Interestingly, even if changes to the current standards were deemed necessary, they would not be due to the needs of older drivers, who were found to have slightly shorter PRT than their younger counterparts.

STOPPING SIGHT DISTANCE

For design purposes, stopping sight distance is the sum of two distances: the distances traversed by the vehicle from the instant the driver sights an object necessitating a stop to the instant the brakes are applied, and the distance required to stop the vehicle from the instant brake application begins. These are referred to as brake reaction distance and braking distance, respectively.[10]

Table 21, extracted from AASHTO's Green Book (1990), shows stopping sight distance for design speeds from 20 to 70 mi/h (32 to 113 km/h).[10] The values are determined from the following formulation:

$$d = 1.47PV + \frac{V^2}{30(f \pm G)} \qquad (1)$$

where P is the brake reaction time, V is the initial speed, f is the coefficient of friction between tires and roadways, and G is the grade, which for the values in table 4.4 is assumed to be zero. The brake reaction time is based on a study which found that 2.5 s was adequate for about 90 percent of the test subjects.[28]

The results of the brake reaction time experiment conducted in this study indicate 85th-percentile brake reaction times as follows:

- All groups -- 1.91 s (n = 56)
- 20-40 age group -- 1.97 s (n = 14)
- 65-69 age group -- 1.92 s (n = 18)
- 70+ age group -- 1.72 s (n = 24)

Somewhat surprisingly, the 85th-percentile reaction times were lower for the older age groups. All of these values are well below the 2.5 s value currently used in the equation above. For comparison purposes, other researchers who have conducted similar type studies arrived at the following conclusions concerning perception-reaction time for stopping sight distance:

- NCHRP Report 270, "Parameters Affecting Stopping Sight Distance" -- 1.6 s for 90th percentile, with an additional 50-percent correction factor (2.4 s) to allow for a driving population that includes persons who are relatively fatigued, less attentive, or whose senses have been dulled by drugs of some kind.

- FHWA Report FHWA/RD-87/015, "Improved Perception-Reaction Times Information for Intersection Sight Distance" -- The 2.5 s assumed for stopping sight distance as applied to Case II yield-controlled intersection is more than adequate for that application.

Table 21. AASHTO stopping distance standards.

Design Speed mi/h (km/h)*	Assumed Speed for Condition mi/h (km/h)*	Stopping Sight Distance Computed ft (m)*	Stopping Sight Distance Rounded for Design ft (m)*
20 (32)	20-20 (32-32)	106.7-106.7 (32.5-32.5)	125-125 (38-38)
25 (40)	24-25 (37-40)	138.5-146.5 (42.2-44.7)	150-150 (46-46)
30 (48)	28-30 (45-48)	177.3-195.7 (54.1-59.7)	200-200 (61-61)
35 (56)	32-35 (52-56)	217.7-248.8 (66.4-75.9)	225-250 (69-76)
40 (65)	36-40 (58-65)	267.0-313.3 (81.4-95.6)	275-325 (84-99)
45 (72)	40-45 (65-72)	318.7-382.7 (97.2-116.7)	325-400 (99-122)
50 (81)	44-50 (71-81)	376.4-461.1 (114.8-140.6)	400-475 (122-145)
55 (89)	48-55 (77-89)	432.0-537.8 (131.8-164.0)	450-550 (137-168)
60 (97)	52-60 (84-97)	501.5-633.8 (153.0-193.3)	525-650 (160-198)
65 (105)	55-65 (89-105)	549.4-724.0 (167.6-220.8)	550-725 (168-221)
70 (113)	58-70 (93-113)	613.1-840.0 (187.0-256.2)	625-850 (191-259)

*mi = km x 0.621, ft = m x 3.28

The selection of the brake reaction time for design becomes a decision in how much a factor of safety should be used. If the sample of 56 braking drivers in this study was considered to be an adequate representation of total driving population, and if the test protocol used reasonably replicated an actual situation where brake reaction was necessary, selecting the value of 2.54 s (the slowest response time observed) would be appropriate. It would be assumed in this case, that the slowest time represents those drivers who are "less attentive" for reasons noted earlier. Alternatively, one could take the 85th-percentile (an arbitrary design level) as the specification alone, or apply a safety factor to account for the "less attentive." A 50-percent safety factor applied to the 85th-percentile value of 1.91 s would yield a 2.87 s specification, and a 25-percent safety factor would yield a 2.39 s specification.

Unfortunately, there is no precedence or guideline for selecting factors of safety in highway design. Some feel that using 85th-percentile observed values is sufficient alone. It would be helpful in making this decision if it was known how accidents are affected by sight distance. Unfortunately, there is no known numerical relationship of accident occurrence to available stopping sight distance.

<u>Effect of Alternate Brake Reaction Times</u>. From the above discussion, the specification for an appropriate brake reaction time could vary from 2.0 to 3.0 s. How the selection of the specification affects stopping sight distances and ultimately certain design features is discussed next.

Table 22 shows the calculated and rounded-up stopping sight distance values for brake reaction time in increments of 0.1 s from the standard of 2.5 s. The minimum design stopping sight distance based on 2.5 s is shown in the second row. For each of the design

Table 22. Change in minimum SSD for changes in BRT.

Design Speed mi/h [km/h]*	30 (28)[1] [48 (45)]		40 (36) [65 (58)]		50 (44) [81 (71)]		60 (52) [97 (84)]		70 (58) [113 (94)]	
Minimum Design SSD ft (m)*	200 (61)		275 (84)		400 (122)		525 (160)		625 (191)	
BRT (s)	Calc. SSD[2]	Design Value[3]	Calc. SSD	Design Value	Calc. SSD	Design Value	Calc. SSD	Design Value	Calc. SSD	Design Value
2.0	157 (48)	175 (53)	241 (74)	250 (76)	344 (105)	350 (107)	464 (142)	475 (145)	571 (174)	575 (175)
2.1	161 (49)	175 (53)	246 (75)	250 (76)	351 (107)	375 (114)	471 (144)	475 (145)	580 (177)	600 (183)
2.2	165 (50)	175 (53)	251 (77)	N/C	357 (109)	375 (114)	479 (146)	500 (153)	588 (179)	600 (183)
2.3	169 (52)	175 (53)	257 (78)	N/C	364 (111)	375 (114)	487 (149)	500 (153)	597 (182)	600 (183)
2.4	173 (53)	175 (53)	262 (80)	N/C	370 (113)	375 (114)	494 (151)	500 (153)	605 (185)	N/C
2.5	178 (54)	200 (61)	267 (81)	275 (84)	376 (115)	400 (122)	502 (153)	525 (160)	613 (187)	625 (191)
2.6	182 (56)	N/C	273 (83)	N/C	383 (117)	N/C	510 (156)	N/C	622 (190)	N/C
2.7	186 (57)	N/C	278 (85)	300 (92)	390 (119)	N/C	517 (158)	N/C	631 (192)	650 (198)
2.8	190 (58)	N/C	283 (86)	300 (92)	396 (121)	N/C	525 (160)	N/C	639 (195)	650 (198)
2.9	194 (59)	N/C	288 (88)	300 (92)	403 (123)	425 (130)	532 (162)	550 (168)	648 (198)	650 (198)
3.0	198 (60)	N/C	294 (90)	300 (92)	409 (125)	425 (130)	540 (165)	550 (168)	656 (200)	675 (206)

[1] Assumed speed for minimum SSD.
[2] Calculated SSD value using minimum speed value.
[3] Design value based on rounding to nearest 25. N/C indicates no change to the design value.
*mi = km x 0.621, ft = m x 3.28

speeds and brake reaction times, a calculated SSD is shown. Under the "Design Value" column is the rounded-up value based on the same rounding-up principle -- nearest 25 ft (8 m) -- applied, for the current standard. An "N/C" means that there would be no change in the design value from the current value. This analyses reveals that if the same 25 ft (8 m) rounding principle were applied a small change in the selected brake reaction time could have a 25 ft (8 m), or more, change in the design value even though the difference based on the calculated value is small. At the low design speed, 30 mi/h (48 km/h), there would be no change in the design value even if the brake reaction time were increased to 3.0 s. However, at the highest design speed, 70 mi/h (113 km/h), a 3.0 s specification would require 50 ft (15 m) more.

SSD is used as a basis for several design elements with vertical curvature being one of the most critical. To provide minimum (or desirable) SSD along the road, vertical curves, especially crest curves, must be designed to provide the sight distance. The formulas provided by AASHTO for determining the length of parabolic vertical curves are in terms of the algebraic difference in grade and sight distance, and are as follows:

(4)

For S<L:

$$L = \frac{AS^2}{100(\sqrt{2h_1} + \sqrt{2h_2})^2}$$

For S>L:

$$L = 2S - \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{A}$$

where	L	=	length of vertical curve, ft
	S	=	sight distance, ft
	A	=	algebraic difference in grades, percent
	h_1	=	height of object above roadway surface = 0.50 ft
	h_2	=	height of eye above roadway surface = 3.50 ft

The sight distance, S, is stopping sight distance. Hence, if the brake reaction time is changed from 2.5 s then the value of L will change as well.[10]

For the purposes of designing parabolic vertical curves, the value K is specified where K = L/A. It is the horizontal distance in feet required to effect a 1 percent change in gradient and is, therefore, a measure of curvature. Table 23 shows the design controls, i.e. - K values, for vertical curves from AASHTO.[10]

Similar to the analysis conducted for minimum SSD, table 24 was prepared to show the change in design K value for various brake reaction time and design speeds. It is observed from this table that the minimum design K value would change for most values of brake reaction time except at the low design speeds. At the low design speed of 30 mi/h (48 km/h) the design K would not change even if the brake reaction time were set at 3.0 s. However, at the highest design speed, the K value would increase significantly.

Since the length of curve, L, determined as a project of K times A, the algebraic difference in grades, the results from table 24 can be used to develop table 25. This table shows the length of curves for different K values and values of brake reaction time. As can be seen by the data, a change in brake reaction time in the order of +/- 0.1 s would not significantly affect the length of curve for most design speeds, but higher increases in brake reaction time would. The practical impact of longer vertical curve length is that crest curves would be less severe and that greater amounts of earth work would be required to achieve the smooth profile. Whether or not the higher construction costs would be out weighed by the possible savings from less accidents and smoother speed profile would need to be established to support a design change.

Table 23. AASHTO K values for crest vertical curves.

Design Speed mi/h (km/h)*	Assumed Speed for Condition mi/h (km/h)*	Coefficient of Friction f	Rate of Vertical Curvature, K (length (ft) per percent of A) Rounded for Design ft (m)*
20 (32)	20-20 (32-32)	0.40	10-10 (3-3)
25 (40)	24-25 (37-40)	0.38	20-20 (6-6)
30 (48)	28-30 (45-48)	0.35	30-30 (9-9)
35 (56)	32-35 (52-56)	0.34	40-50 (12-15)
40 (65)	36-40 (58-65)	0.32	60-80 (18-24)
45 (72)	40-45 (65-72)	0.32	80-120 (24-37)
50 (81)	44-50 (71-81)	0.30	110-160 (34-49)
55 (89)	48-55 (77-89)	0.30	150-220 (46-67)
60 (97)	52-60 (84-97)	0.29	190-310 (58-95)
65 (105)	55-65 (89-105)	0.29	230-400 (70-122)
70 (113)	58-70 (93-113)	0.28	290-540 (88-165)

*mi = km x 0.621, ft = m x 3.28

DECISION SIGHT DISTANCE

As a geometric design element, decision sight distance is intended to provide sufficient sight distance for a driver to detect an unexpected or otherwise difficult to perceive information source or hazard, recognize the hazard or its threat potential, select an appropriate speed and path, and initiate and complete the required maneuver safely and efficiently.[10] Because DSD is defined to provide for a less restrictive maneuver than the sudden braking assumed for SSD, DSD values are substantially greater. This sight distance was established for complex driving situations such as interchanges, lane drops, high-speed merges, and intersections where unusual maneuvers are required.

AASHTO's 1984 Green Book identifies the three components of DSD: (1) the detection and recognition time, (2) the decision and response initiation time, and (3) the maneuver time.[12] The first two components comprise the perception-reaction time while the third is the time required to actually perform the maneuver. The 1990 edition of the Green Book assumes the following values for these components for urban facilities (Note: Our DSD PRT experiment was conducted primarily on urban freeways and arterials.[10] Our analysis will therefore

Table 24. Change in K value for changes in BRT.

Design Speed mi/h [km/h]*	30 (28)[1] [48 (45)]		40 (36) [65 (58)]		50 (44) [81 (71)]		60 (52) [97 (84)]		70 (58) [113 (93)]	
Minimum Design K (L/A) ft (m)*	30 (9)		60 (18)		110 (34)		190 (58)		290 (88)	
BRT (s)	Calc. K[2]	Design Value[3]	Calc. K	Design Value	Calc. K	Design Value	Calc. K	Design Value	Calc. K	Design Value
2.0	18.5 (5.6)	20 (6)	43.6 (13.2)	50 (15)	89.3 (27.2)	90 (27)	162.0 (49.4)	170 (52)	245.3 (74.8)	250 (76)
2.1	19.5 (5.9)	20 (6)	45.6 (13.9)	50 (15)	92.7 (28.3)	100 (31)	167.2 (51.0)	170 (52)	252.7 (77.1)	260 (79)
2.2	20.5 (6.3)	N/C	47.6 (14.5)	50 (15)	96.1 (29.3)	100 (31)	172.6 (52.6)	180 (55)	260.2 (79.4)	270 (82)
2.3	21.6 (6.6)	N/C	49.6 (15.1)	50 (15)	99.6 (30.4)	100 (31)	178.2 (54.4)	180 (55)	267.8 (81.7)	270 (82)
2.4	22.6 (6.9)	N/C	51.7 (15.8)	N/C	103.2 (31.5)	N/C	183.8 (56.1)	N/C	275.5 (84.0)	280 (85)
2.5	23.7 (7.2)	30 (9.2)	53.6 (16.3)	60 (18)	106.6 (32.5)	110 (34)	189.2 (57.7)	190 (58)	282.8 (86.3)	290 (88)
2.6	24.8 (7.6)	N/C	55.9 (17.0)	N/C	110.5 (33.7)	120 (37)	195.0 (59.5)	200 (61)	291.3 (88.8)	N/C
2.7	26.0 (7.9)	N/C	58.1 (17.7)	N/C	114.3 (34.9)	120 (37)	201.3 (61.4)	210 (64)	299.3 (91.3)	300 (92)
2.8	27.1 (8.3)	N/C	60.3 (18.4)	70 (21)	118.1 (36.0)	120 (37)	207.3 (63.2)	210 (64)	307.4 (93.8)	310 (95)
2.9	28.3 (8.6)	N/C	62.6 (19.1)	70 (21)	122.0 (37.2)	130 (40)	213.3 (65.1)	220 (67)	315.7 (96.3)	320 (98)
3.0	29.5 (9.0)	N/C	64.9 (19.8)	70 (21)	126.0 (38.4)	130 (40)	219.5 (66.9)	220 (67)	324.1 (98.9)	330 (101)

[1] Assumed speed for minimum SSD.
[2] Calculated K value using minimum speed value.
[3] Design value based on rounding to nearest 10. N/C indicates no change to the design value.
*mi = km x 0.621, ft = m x 3.28

Table 25. Change (percent) in minimum length of curve (l) for different design speeds and BRT.

Design Speed mi/h (km/h)*	30 (48)	40 (65)	50 (81)	60 (97)	70 (113)
Minimum Design K (L/A) ft (m)*	30 (9)	60 (18)	110 (34)	190 (58)	290 (88)
BRT (s)	Change (percent) from Current Design Standard[1]				
2.0	-33.3%	-16.7%	-18.2%	-10.5%	-13.8%
2.1	-33.3%	-16.7%	-9.1%	-10.5%	-10.3%
2.2	0%	-16.7%	-9.1%	-5.3%	-6.9%
2.3	0%	-16.7%	-9.1%	-5.3%	-6.9%
2.4	0%	0%	0%	0%	-3.4%
2.5	0%	0%	0%	0%	0%
2.6	0%	0%	9.1%	5.3%	0%
2.7	0%	0%	9.1%	10.5%	3.4%
2.8	0%	16.7%	9.1%	10.5%	6.9%
2.9	0%	16.7%	18.2%	15.8%	10.3%
3.0	0%	16.7%	18.2%	15.8%	13.8%

[1] Percent change in Design L Value vs. AASHTO Minimum Design L Value; Zero percent (0%) indicates no change in Design L Value.
*mi = km x 0.621, ft = m x 3.28

focus on the AASHTO DSD standards for "Avoidance Maneuver E - Speed/path/direction change on an urban road" described in table 26, taken from table III-3 of the 1990 Green Book.[10]

Table 26. Assumed PRT & maneuver times for AASHTO DSD standards (urban roads).

Design Speed mi/h (km/h)*	Detection & Recognition (s)	Decision & Response Initiation (s)	Maneuver (s)	Total (s)
30 (48)	3.0	6.5	4.5	14.0
40 (65)	3.0	6.5	4.5	14.0
50 (81)	3.0	6.5	4.5	14.0
60 (97)	3.0	7.0	4.5	14.5
70 (113)	3.0	7.0	4.0	14.0

*mi = km x 0.621

As was discussed in chapter 3, the DSD experiment yielded the median and 85th-percentile values for the PRT components shown in table 27. The 85th-percentile PRT values for all age groups fell well within the AASHTO standards for both freeway and arterial situations. The 7.6 to 7.8 s PRT for all age groups in freeway situations were well within the AASHTO standard of 10.0 s. For arterial situations, the PRT for all age groups were also well within the AASHTO standard of 9.5 s, the longest being the 85th-percentile PRT for the 65-to-69 group of 7.6 s, 1.9 s less than the recommended value of 9.5 s.[10]

Table 27. 50th- and 85th-percentile PRT by age, situation type, and day/night condition.

	Freeway PRT (s)				Arterial PRT (s)			
	50th %		85th %		50th %		85th %	
Age Group	Day	Night	Day	Night	Day	Night	Day	Night
20-40	2.9	3.8	7.8	7.1	2.0	2.8	4.2	5.2
65-69	3.9	3.8	7.6	6.7	2.8	2.4	7.6	4.9
70+	4.2	4.0	7.8	7.0	3.4	2.8	7.1	5.6
AASHTO			10.0				9.5	

In deciding if any changes to the AASHTO values are needed, the issue becomes whether or not the 85th-percentile values represent acceptable standards. While the 85th-percentile values measured in our experiment do lie within the AASHTO standards, it should be remembered that the experimental values did not necessarily include the response initiation component of the PRT assumed in AASHTO. Taking this into account, it could be argued that an additional safety factor should be applied to the DSD values. As was discussed in the previous section on SSD, the 85th-percentile is an arbitrary design value. One could, for instance, use the slowest observed PRT value as the design standard to ensure that the full spectrum of drivers are covered. Alternatively, one could apply a safety factor of 10 percent to 50 percent to the 85th-percentile values in order to guarantee a sufficient margin for error.[10]

<u>Effect of Alternate Perception-Reaction Times</u>. Using the slowest observed PRT as a standard would be impractical in this case as there were some measured values as high as 20 s. It is not felt that these represent realistic PRT. Alternatively, we could look at the highest 85th-percentile value at any *one* site, take it as the standard, and apply a safety factor to it. The longest 85th-percentile value at any site (excluding sites 10 and 13, which were dropped because of inconsistent data) was 9.7 s for the 65-to-69 age group at site 12. A 50-percent safety factor for the 9.7 s PRT would mean adding an additional 4.75 s. Table 28 shows the effects of increasing the PRT on the decision sight distance standards (these values are for "Avoidance Maneuver E - urban roads" only).

Table 28. Effect of increasing PRT on decision sight distance (urban facilities).

Design Speed mi/h (km/h)*	AASHTO DSD ft (m)*	Δ PRT				
		+1.0 s	+2.0 s	+3.0 s	+4.0 s	+5.0 s
30 (48)	625 (191)	675 (206)	700 (214)	750 (229)	800 (244)	850 (259)
40 (65)	825 (252)	900 (275)	950 (290)	1000 (305)	1075 (328)	1125 (343)
50 (81)	1025 (313)	1100 (336)	1175 (358)	1250 (381)	1325 (404)	1400 (427)
60 (97)	1275 (389)	1375 (419)	1450 (442)	1550 (473)	1650 (503)	1725 (526)
70 (113)	1450 (442)	1600 (488)	1700 (519)	1800 (549)	1900 (580)	2025 (618)

*mi = km x 0.621, ft = m x 3.28

It can be seen that increasing the PRT by a 5-s (≈50 percent) safety factor would result in substantial increases in decision sight distances. The increases would range from 225 to 575 ft (69 to 175 m) depending on the design speed. Even a 2.0 s (≈20 percent) increase in PRT would produce increases in DSD of 75 to 250 ft (23 to 76 m). The question now becomes what factor of safety is appropriate? There is unfortunately no established empirical relationship between accident occurrence and available decision sight distance and the choice therefore becomes somewhat subjective.

With this in mind, there are two issues that need to be examined. First, the provision of longer decision sight distances does not necessarily mean that drivers are able to make full use of them. There are limits to the distances at which drivers can visually detect objects or hazards, and this is particularly true for older drivers whose vision is often deteriorated.

Furthermore, a previous study found that the use of excessively long sight distances does not dramatically enhance safety because drivers simply use the extra distance to delay their maneuver.[11]

Second, current decision sight distance standards have not been universally adopted by the States because the costs of providing longer sight distances have not been justified.[41] Increased decision sight distance standards that can not be justified in terms of improvements to safety are not likely to be adopted by the States, and could in fact prove counter-productive if it further discourages States from adopting the standards.

It is therefore felt that no modifications to the existing DSD standards are necessary. The current standards are adequate to cover more than 85 percent of the 70+ age group and an even greater percentage of the population as a whole. Increasing decision sight distance standards to account for the "least attentive" drivers would not be likely to significantly enhance safety and would be very difficult to justify in terms of increased costs.

CHAPTER 5. ALTERNATIVE MODELS

All of the standard sight distance models are based on the same principle. A certain value of PRT is multiplied by the appropriate design speed and then the maneuver component (e.g., stopping distance) is added to arrive at the sight distance. The PRT values have been developed mostly from a sequential information processing model which assumes that drivers perform tasks in a serial process of detection, perception, decision, and response. Human factors researchers recognize that these tasks are really not performed sequentially, but in driving behavior research it is nearly impossible to identify the overlaps. Some researchers have therefore offered alternative approaches for determining sight distances. One such approach that has been raised by several researchers is the use of gap acceptance times for determining Case III intersection sight distances. The premise here is that there is a minimum gap time between approaching vehicles that the design driver needs to turn left, right, or go straight. This gap value can then be applied to the design speed to determine the appropriate sight distance for a given intersection.

<u>Gap Acceptance Model</u>. The results of the gap/lag Acceptance experiment are discussed in chapter 3. A gap acceptance model for determining intersection sight distances would assume some minimum gap value that drivers require to perform a specific maneuver. This gap time would then be multiplied by the design speed to yield the appropriate sight distance. Several studies have examined gap acceptance times at stop controlled intersections. The results of some U.S. studies are summarized in table 29 below.[49]

Table 29. Results of selected gap acceptance studies.

Study	Maneuver	Critical Gap
Greenshield (1947)	Crossing	6.1 s
Raff (1950)	Crossing	6.1 s
Bissell (1960)	Crossing	5.8 s
Polus (1983)	Right	7.5 s
Solberg & Oppenlander (1966)	Left	7.8 s (50%)
	Crossing	7.2 s (50%)
	Right	7.4 s (50%)
Fitzpatrick (1991)	Left	6.5 s (50%)
	Crossing	7.8 s (50%)
	Right	6.5 s (50%)
Current Study	Left	7.6 s (50%)
	Crossing	6.9 s (50%)
	Right	7.4 s (50%)
Highway Capacity Manual	Left	6.5 - 8.0 s
	Crossing	6.0 - 7.5 s
	Right	5.5 - 6.5 s

The median gap acceptance values from this experiment are also included in the table. The results from this experiment are in general agreement with other gap acceptance studies. It should be kept in mind, however, that different methods for determining the "critical gap" were used for each study, so the results are not all directly comparable. It should also be remembered that the data collection methods and conditions differed for each study. Factors such as major road speed, traffic volumes, and intersection geometry have all been shown to affect gap acceptance times.

Table 29 also presents critical gap values for unsignalized intersections that are taken from the Highway Capacity Manual (table 10-2).[50] The values shown are for 2-lane roads; the lower value is for the 30 mi/h case and the higher value for the 55 mi/h case. The empirical and computational basis for these values is not clear from the Manual. The findings of the present experiment fall between the lower- and higher-speed Manual values for the left turn and crossing maneuvers. The current study obtained right turn maneuver values about 1 s longer than those shown for the high-speed road in the Highway Capacity Manual.[50]

What needs to be determined for a gap acceptance model is exactly what gap value constitutes the "critical gap" to be used to compute intersection sight distances. Median values represent gaps acceptable to only 50 percent of test drivers and would probably be insufficient for design standards. Although it is somewhat arbitrary, gap values that were acceptable to 85 percent of test drivers will be used as the "critical gaps" for this analysis.

Looking at the daytime data (when gap acceptance times were longest), the 85th-percentile values for gaps accepted at both study sites were 11.0 s for left turns, 9.5 s for right turns, and 9.8 s for crossing maneuvers. (By comparison, the 85-percent probabilities for gap acceptance in the Fitzpatrick study were 8.3 s for left and right turns and 10.5 s for crossing maneuvers.)[49] If one assumes these gaps represent the minimum times required for Case III turn movements, then equivalent sight distances can be computed by multiplying the gap acceptance times by the design speeds. Table 30 below summarizes intersection sight distances for both the low and high-speed sites based on gap acceptance values and compares them with current AASHTO standards.[10]

Table 30. Intersection sight distances based on gap acceptance model.

		Low Speed			High Speed		
Maneuver	Critical Gap (s)	Gap ISD ft (m)*	AASHTO ft (m)*	Δ ISD (%)	Gap ISD ft (m)*	AASHTO ft (m)*	Δ ISD (%)
Left	11.0	485 (148)	380 (116)	+22%	810 (247)	840 (256)	-4%
Crossing	9.8	430 (131)	295 (90)	+46%	720 (220)	480 (146)	+50%
Right	9.5	420 (128)	380 (116)	+11%	700 (214)	840 (256)	-17%

*mi = km x 0.621, ft = m x 3.28

Looking first at the left turns, it can be seen that the 85-percent gap acceptance values yield intersection sight distances that are considerably longer than the AASHTO standard at the low-speed site (+22 percent) but slightly shorter than the AASHTO value at the high-speed site (-4 percent). Right-turn sight distances are 10 percent higher than the AASHTO standard at the low-speed site but 17 percent lower at the high-speed site. These values appear to be within a reasonable range of current AASHTO standards; however, since drivers did not actually perform any maneuvers in this study, there is no data with which to evaluate how accurately these reflect driver needs.

Although the left- and right-turn gap values may warrant further examination, other gap ISD findings raise some questions about the validity of the gap acceptance model. This is most apparent in the gap ISD values for crossing maneuvers. These values were nearly 50 percent longer than the AASHTO standards at both sites. AASHTO sight distances for crossing maneuvers are considerably shorter than the sight distances for turning maneuvers because crossing vehicles simply traverse the major roadway and do not need to accelerate up to design speeds. However, the gap acceptance experiment found that the gaps drivers required for crossing maneuvers were not significantly shorter than those required for turning maneuvers and were in many cases longer. This pattern has also been found in other gap acceptance experiments (see table 29). AASHTO crossing maneuver times for two-lane roads (approximately 4.0 to 5.0 s) were confirmed in the Case III ISD experiment and otherwise seem reasonable. For whatever reasons, drivers seem to desire gaps for crossing maneuvers at least as great as those for turning maneuvers even though the actual maneuver times may be much shorter. This raises a question about what portion of an accepted gap reflects real driver needs and what portion reflects driver safety margins. It should be remembered that the test drivers in this experiment were not actually performing maneuvers but were merely responding to a series of gaps over a 10-minute period. Studies have shown that while drivers may have a minimum preferred gap time, that time decreases as the driver is forced to wait at an intersection.[51] Thus a driver who has just arrived at an intersection may initially desire a 10-s gap to make a turn, but after waiting for a minute or longer may be willing to accept a 5- or 6-s gap. It can only be assumed that since the test subjects were not under any pressure to actually make a maneuver, their gap times are probably more indicative of optimum desirable conditions than real-world driving situations.

An examination of the lag rejection data reveals that drivers were willing to accept a median margin for rejection of a lag of only 4.6 s for crossing maneuvers. This is more in line with the AASHTO standard, which assumes a maneuver time of about 4.5 s for crossing a two-lane road. The 85-percent lag rejection value for a crossing maneuver was 6.5 s, considerably shorter than the 9.8 s value found for gap acceptance. Similar results were found for the left and right turn maneuvers, with 85-percent lag rejection values roughly 2.0 s shorter than the corresponding gap acceptance values. Some studies had found little or no difference between gap and lag values, but this does not appear to be the case with this experiment.[49] Whether these differences are caused by difficulties in judging two vehicles at once or other reasons is not clear, however it does raise some question as to whether gap or lag values should be the basis for a sight distance model.

The usefulness and validity of a gap acceptance model are not yet clear. The results of the gap acceptance experiment may indicate that there are differences between what sight distances drivers would like to have, what sight distances they are ultimately willing to accept, and what sight distances they really need to safely perform a maneuver. This is most apparent in the gap acceptance times for crossing maneuvers, which were substantially longer than the times actually required to perform a crossing maneuver. This is also apparent in the results for older drivers, and specifically for those from the 70+ age group, who were found to require longer sight distances than younger drivers even though they do not seem to require longer maneuver times. What gap values should be used and whether these extra margins of safety should be reflected in sight distance standards is somewhat questionable. It is not known whether gap acceptance alone represents the best way to model actual sight distance needs. Alternative gap/lag models may need to be examined.

Lag Rejection Model. The lag rejection point measured in this experiment represents the minimum time for which drivers felt that they could still safely perform a maneuver. When determining the lag rejection point, subjects were monitoring just a single approaching vehicle as opposed to two approaching vehicles for gap acceptance. Because it more accurately models the type of speed/gap judgements used in intersection sight distance, it could be argued that the lag rejection time better reflects the minimum needs of drivers to perform a crossing or turning maneuver and should therefore be used instead of the gap acceptance value to compute required sight distances. An 85th-percentile lag rejection point, for instance, could be multiplied by the design speed to obtain the minimum sight distance requirements for any intersection.

Use of the lag rejection time alone, however, would probably be insufficient to provide adequate sight distances for Case III intersection maneuvers. When subjects in the experiment determined that an approaching vehicle had come too close to permit a safe maneuver, they had already been monitoring that vehicle for several seconds and had been able to estimate that vehicle's speed with some certainty. The lag rejection point measured in the experiment then really represents the minimum time in which subjects felt that they could perform a maneuver, since no additional perception or reaction time would be necessary. In actual sight distance situations, drivers would need some perception-reaction time in addition to this lag time in which to recognize an oncoming vehicle, estimate its approach speed, and decide whether or not a maneuver could be safely performed.

Lag Rejection Plus PRT Model. Some type of model in between the gap acceptance and lag rejection models might be appropriate for determining Case III intersection sight distance standards. The model would take the basic form of:

$$ISD = 1.47V(J + t_{LR}) \tag{6}$$

where ISD is the intersection sight distance in feet, V is the design speed of the major highway in mi/h, J is a perception-reaction time value in seconds, and t_{LR} is a design value for lag rejection time for a given maneuver. This equation is of the same basic form as the equation AASHTO uses to determine crossing sight distances. It substitutes the variable t_{LR} (minimum lag rejection time) for AASHTO's t_a (computed maneuver time).[10] It is in effect the very type of sequential model that the gap acceptance model was intended to replace and it may be argued that reverting back to this type of model defeats the entire purpose of using gap acceptance. We have nonetheless computed some sight distances based on this model to compare with the current AASHTO model.[10]

Using the perception-reaction time (J) value of 2.0 s which was confirmed in the Case III ISD experiment, and adding to it the 85th-percentile lag rejection values for the oldest driver group (since theirs were the slowest), one would obtain the sight distances for Case III maneuvers shown in table 31. The ISD value obtained for the low-speed site is less than that obtained using the gap acceptance model, but still larger than the AASHTO standard. The value for the high-speed site is considerably less than the AASHTO value. The ISD values obtained for all maneuvers at the low-speed site are less than those obtained using the gap acceptance model, but still larger than the AASHTO standards. The left and right turn ISD values obtained for the high-speed site are considerably less than the AASHTO values, although the ISD value for the crossing maneuver is considerably higher than the AASHTO value. In fact, both the gap acceptance and lag rejection plus PRT models yield ISD values for crossing maneuvers substantially higher than the current AASHTO standard. Again, since no maneuvers were performed there is no data with which to evaluate these numbers. Further experimentation will be needed to determine if the use of lag values offers any advantages over the current AASHTO model.[10]

Table 31. Intersection sight distances based on lag rejection + PRT model.

			Low Speed			High Speed		
Maneuver	J (s)	t_{LR} (s)	ISD ft (m)*	AASHTO ft (m)*	Δ ISD (%)	ISD ft (m)*	AASHTO ft (m)*	Δ ISD (%)
Left	2.0	6.8	390 (119)	380 (116)	+3%	650 (198)	840 (256)	-22%
Crossing	2.0	6.6	380 (116)	295 (90)	+29%	650 (198)	480 (146)	+35 %
Right	2.0	7.9	435 (133)	380 (116)	+14%	730 (223)	840 (256)	-13%

*ft = m x 3.28

It may also be noted that the lag rejection plus PRT model yields total times ($J + t_{LR}$) for left turn and crossing maneuvers that exceed the critical gap values provided in the Highway Capacity Manual for high speed, two-lane roads. The model values slightly exceed the manual values for four-lane roads. The total time for right turn maneuvers under this model considerably exceeds the Highway Capacity Manual values.

<u>Conclusions</u>. It is not clear which, if any, of the gap/lag acceptance models represent the best way to model intersection sight distance needs. Nor is it clear whether these models offer any significant benefits over the current AASHTO model, especially in light of the fact that the Case III ISD experiment found AASHTO perception-reaction time values to be

adequate for the full driving population.[10] Questions concerning crossing sight distances, differences between gap and lag data, and age differences in gaps accepted will need to be addressed before the validity of gap/lag models can be assessed. There are additional questions not raised in this study that will also have to be addressed. If traffic volumes and delay also affect gap acceptance, then what gap acceptance values should be used as the "critical gaps"? Does roadway speed have an effect on gap acceptance? Although this study did not find speed to be a significant factor in gap acceptance, that conclusion is based on only two sites and other studies have found that speed does impact gap acceptance. We have developed a preliminary research plan to investigate some of these questions.

CHAPTER 6. SUMMARY

Current sight distance models share a similar principle, which assumes there is a sequential process of perceiving an event and initiating a response to it (PRT), and then executing the desired maneuver. In the sight distance equation, an assumed value of PRT is multiplied by the design speed and then the maneuver component is added to arrive at the required sight distance. For any of these sight distance situations, then, PRT is an important component. If the design PRT values are less than those actually required by a driver, design practices may place that driver at risk. For this reason, there has been special concern about the adequacy of PRT assumptions with regard to older drivers. As the literature review of chapter 2 indicated, there is a very general slowing of all of the component psychological processes that underlie PRT. Yet there has been little direct evidence of slower driver PRT for older motorists under actual driving conditions, and little objective basis for making a comparison of actual PRT with the assumed design values. The sequence of experiments reported here was designed to provide realistic, on-the-road PRT data for three important sight distance situations: Case III ISD, DSD, and DSD. These data allowed a consideration of the adequacy of the values used in current design equations, as well as the consideration of alternative models.

Although there were a number of differences between age groups observed in the various experiments, overall there was not a sense of dramatically slower PRT for older drivers, nor an indication of clearly inadequate design values. For the perceptually and/or operationally complex DSD situations, older drivers did have slower PRT, but there was little difference for SSD or ISD situations. These observations are consistent with those of the few other on-road experiments that have compared the PRT of older and younger drivers. Older drivers generally appear capable of maintaining adequately rapid responding, even if the mechanisms by which they compensate for reduced underlying capabilities are not entirely clear. Considering the findings and implications of each of the experiments of this study, the following general conclusions can be made:

- **Case III Intersection Sight Distance** - The current AASHTO standard of 2.0 s for PRT (J) approximates the 85th-percentile J values obtained in this experiment and appears to adequately cover the full driving population, and in particular older drivers. The 85th-percentile PRT values were actually shorter for the older groups than for the younger group. No experimental PRT value was more than 20 percent greater than the 2.0-s standard and some were as much as 20 percent lower. Considering that the experimental procedure probably represented a worst-case scenario for visual search and detection and that one would therefore expect slightly higher values than would be found in "normal" driving practice, it is not felt that any modifications to the current intersection sight distance PRT standards are necessary.[10]

- **Stopping Sight Distance PRT** - The 85th-percentile PRT values for brake reaction time for all age groups were well within the current 2.5 s AASHTO standard, which captured essentially all responses. The experimental 85th-percentile PRT values were 1.72, 1.92, and 1.97 s for the 70+, 65-to-69, and

20-to-40 age groups respectively. Although some have suggested that an additional safety margin be included in the PRT, there is unfortunately no precedence for selecting factors of safety in highway design. The current standard appears to adequately cover the full driving population, and older drivers in particular. No change to the current 2.5-s standard is being recommended.[10]

- **Decision Sight Distance** - Although older drivers were found to have longer PRT in decision sight distance situations, the 85th-percentile PRT values were within the current AASHTO standards for both freeway and arterial situations. The older groups had 85th-percentile PRT of 7.8 s for freeway situations and 7.2 s for arterials, both well within the current AASHTO standards of 10.0 and 9.5 s respectively. The 85th-percentile total times (PRT plus maneuver) were found to be longer than the current standards, but this was due primarily to the fact that the experiment was conducted under heavier traffic conditions than those assumed in AASHTO and maneuver times were therefore longer. It is not felt that any changes to the current PRT standards are necessary.[10]

- **Gap/Lag Acceptance** - It is not clear whether a gap acceptance model for determining intersection sight distances offers any significant advantages over the current AASHTO model. Intersection sight distances based on 85-percent gap acceptance values were found to be longer than AASHTO standards for left and right turns at the low-speed site, but shorter at the high-speed site. The results of the gap acceptance experiment also raised several questions that will need to be examined before the validity of a gap acceptance model can be determined: (1) Sight distances based on gap acceptance for crossing maneuvers were found to be nearly 50 percent longer than the current AASHTO standards at both sites. The reason for this dramatic difference will need to be examined. Furthermore, crossing sight distances based on gap acceptance are not significantly shorter than left and right turn sight distances, even though the actual maneuver times are considerably less. (2) The gap acceptance study found that drivers in the oldest group required longer gaps than the younger group. This is in contrast to the findings of the Case III intersection PRT experiment which found no significant differences between the total maneuver times of older and younger drivers. (3) Drivers of all age groups had mean lag rejection times nearly 2.0 s shorter than the mean gap acceptance times. This raises some question as to whether gap acceptance or lag rejection times should be used to compute intersection sight distances. In summary, it appears that further research will need to be performed to determine the validity of a gap/lag acceptance model and what advantages, if any, such a model would offer over the current AASHTO model.[10]

Overall, it would appear that <u>to the extent current models are reasonable and appropriate analogues</u> of actual driver behavior, the PRT design parameters of those models are generally adequate to accommodate most older drivers. Of course, increases in sight distance requirements might provide some increments in driver safety, even if marginal. The precise relationship of sight distance values to actual safety benefits is not well defined. As chapter 4 indicated, arguments can be made for more conservative criteria. However, the research findings and analysis presented here do not favor that conclusion.

We do not wish the findings of these experiments to be taken to imply that there are not older drivers for whom there are driving performance problems and for whom some design standards may be inadequate. In fact, one can point to specific subgroups for whom there are known problems, such as those suffering early stage Alzheimer's disease. Due to health status or various perceptual, cognitive, or motor deficits, some older drivers will have significantly slower PRT as well as other serious driving problems. Even though efforts were made to minimize the self-selection bias inherent in any study using cooperating subjects, there is little doubt that those who felt least capable probably did not take part. However, what is most important is that problems with sufficiently rapid responding (relative to highway design practice) do not appear to characterize the broad range of older drivers. Furthermore, those with the poorest capabilities select themselves out of the driving population, and at the least certainly account for far fewer driving miles than their more typical age peers.[52,23] One might always argue that highway design practices should encompass even the most extreme cases, or for adding a greater "factor of safety" (multiplier) in moving from observed behavior to design equations. However, it does appear that current assumptions about driver PRT provide a reasonable match to the typical range of performance of those older people using the roadways. Older drivers may be maintaining this performance through some sorts of compensatory mechanisms, which may have other driving implications; they may feel less comfortable with various temporal demands; they may be more prone to suffer delayed responding if they are in severe informational "overload" situations; and there may not be a good match of some design and operational practices to other aspects of older driver performance. However, although accident evaluations and various driving studies indicate that older drivers, as a group, do suffer various driving problems, it does not appear that inappropriately brief PRT design values, in themselves, are a major concern.

The research conducted under the project reported here is one of many efforts addressing issues related to older drivers. In order to facilitate comparisons with other studies, table 32 identifies broad issues that cut across projects. The table indicates the parts of this report that address key cross-cutting problems.

Table 32 Crosscutting issues addressed in this report

Report Section	Broad Issues						
		Functional abilities					
	Age groupings, subject selection	Sensory/ perceptual function	Cognitive and attentional process	Psychomotor, speed of behavior	Accident characteristics	Compensation for age effects	Applications, countermeasures, design implications
INTRODUCTION				p. 2	p. 1		
LITERATURE REVIEW		p. 11	p. 11	pp. 9-10 pp. 12-14	pp. 15-16		
RESEARCH STUDIES	p. 22			pp. 25-31 pp. 35-41 p. 43 pp. 48-56		p. 33 pp 44-45 p. 70-71	pp. 31-33 p. 42
IMPLICATIONS FOR EQUATIONS							pp. 73-87
ALTERNATIVE MODELS							pp. 89-94
SUMMARY	p. 97			p. 96		p. 97	pp. 95-96

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